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Edited for the Council by J. LAURENCE PRITCHARD, Honorary Fellow

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NOTICES

Election of Members

The following members were elected at a Council Meeting held on March 11th:—

Associate Fellows.—Flight Lieut. P. W. S. Bulman, M.C., A.F.C., Mr. James Calderwood and Mr. Norman Rowbotham.

Students.—Mr. M. S. Hooper and Mr. D. R. L. Strang.

Associate Member.—Captain A. C. Day, F.C.I.P.A.

Wilbur Wright Lecture

Lieut.-Colonel H. T. Tizard, A.F.C., Fellow, has accepted the Council's invitation to deliver the Wilbur Wright Memorial Lecture. This will take place at 8.30 p.m., on Thursday, May 29th, at the Royal Society of Arts, John Street, Adelphi, the subject being "Fuel Economy in Flight." This will be the twelfth lecture in memory of Wilbur Wright, who died on May 30th, 1912, delivered under the auspices of the Society and the Trustees of the Wilbur Wright Memorial Lecture Fund. The full list of previous lectures is as follows:—

1913 Sir Horace Darwin, F.R.S., "Scientific Instruments: Their Design and Use in Aeronautics."
1914 Sir R. T. Glazebrook, F.R.S., "The Development of the Aeroplane."
1915 Professor G. H. Bryan, F.R.S., "The Rigid Dynamics of Circling Flight."
1916 Mr. Griffith Brewer, "The Life and Work of Wilbur Wright."
1917 Lieut.-Colonel M. O'Gorman, C.B., "Looking Ahead."
1918 Dr. W. F. Durand, "Some Outstanding Problems in Aeronautics."
1919 Professor L. Bairstow, F.R.S., "Progress of Aviation in the War Period."
1920 Commdr. J. C. Hunsaker, U.S.N., "Naval Architecture in Aeronautics."
1921 Mr. G. I. Taylor, F.R.S., "Scientific Methods in Aeronautics."
1922 Lieut.-Colonel A. Ogilvie, C.B.E., "Some Aspects of Aeronautical Research."
1923 Professor J. S. Ames, "The Relation between Aeronautic Research and Aircraft Design."

Associate Fellowship Qualifications

In view of misapprehensions which appear to exist as to the necessity for taking the Society's examination for Associate Fellowship, attention is called to Clause IX. of the Regulations, which reads as follows:—

"IX.—EXEMPTIONS FROM THE WHOLE OF THE EXAMINATION.

Any of the following qualifications will exempt a candidate from the whole of the examination:—

XIIM

(*a*) Any engineering degree, with advanced mathematics, of any University in the United Kingdom or in the British Dominions overseas. If the degree be without advanced mathematics, a further qualification of equivalent value will be required, or the candidate be required to take the Mathematics Section of the Examination of the Society.

(*b*) The diploma in aeronautics at the Imperial College of Science and Technology, or the Cambridge B.A. in aeronautics.

(*c*) Whitworth Scholarships.

(*d*) The engineering diplomas of the Imperial College of Science and Technology, and of other Schools of Technology under the conditions relating to (*a*).

FROM PART I.

(*e*) Matriculation at a University or equivalent examination; a science degree from any University of the United Kingdom or the British Dominions; or having obtained a Whitworth Exhibition; or having passed into R.N. College, Osborne, R.N.E. College, R.M.A., R.M.C., or R.A.F. College, Cranwell.

OTHER EXEMPTIONS.

The Council will consider on its merits any other degree, diploma or certificate of equivalent standing to those enumerated above which may have been obtained by a candidate from any University or College in the United Kingdom or abroad."

Library

The following books have been recently received and placed in the Library:—"Transport and its Indebtedness to Science," Sir Henry Fowler; "Flying," Major W. T. Blake; "The Aircraft Year Book," edited by C. G. Grey and C. Lee; "Las Escursiones Aerostaticas," Julio Verne; "El Primer Libro Impreso Sobre Aviacion es Espanol?" V. Castaneda Y Alcover; "Les Progrès de l'Aviation depuis 1891 par le vol plané," F. Ferber; "Les Progrès de l'Aviation par le vol plané. Les calculs," F. Ferber; "Forecasting Weather," 2nd Edition, Sir Napier Shaw; "Over the Balkans and South Russia," H. A. Jones; "Catalogue de la Bibliothèque de l'Aéro Club de France" "Elementary Aeronautical Science," I. B. Hart and W. Laidler; "The Mechanical Properties of Fluids," various authors; "The History and Progress of Metallurgical Science," Sir Robert Hadfield; "Taschenbuch der Luftflotten, 1923," von Langsdorff; "Funktelegraphische Wetter-und-Zeitzeichendienst," H. Thurn; "Ergebnisse . . . zu Göttingen," Prandtl, etc.; "Report of the Air Survey Committee, No. 1," The War Office; and "The Technical Report of the Advisory Committee for Aeronautics, 1919-1920."

The Effect of Meteorological Conditions on Airships

Fig. 3 of this paper, which appeared on page 214 of the March issue, was reproduced by permission of His Majesty's Stationery Office.

Forthcoming Arrangements

Thursday, April 3rd, 5.30 p.m.—Colonel the Master of Sempill, A.F.C., Associate Fellow, "The British Aviation Mission to the Imperial Japanese Navy," at the Royal Society of Arts.

Tuesday, April 15th, 5.30 p.m.—Council Meeting.

Thursday, May 29th, 8.30 p.m.—**Wilbur Wright Lecture.** Lieut.-Colonel H. T. Tizard, "Fuel Economy in Flight," at the Royal Society of Arts.

W. LOCKWOOD MARSH, *Secretary.*

THE ROYAL AERONAUTICAL SOCIETY

ANNUAL GENERAL MEETING

The Fifty-ninth Annual General Meeting of members of the Society was held in the Society's offices, 7, Albemarle Street, W., at 5 p.m. on Thursday, March 27th, 1923; the Chairman, Lieutenant-Colonel A. Ogilvie, C.B.E., presiding.

Colonel the Master of Sempill, Mr. A. E. Turner, and Mr. F. P. Walsh were appointed scrutineers of the ballot for the election of new members to the Council.

The minutes of the last Annual General Meeting were taken as read and confirmed.

The Council's report for the year 1923-1924, and the Balance Sheet and Accounts as published in the March issue of the Journal were adopted on the proposal of Professor Bairstow, seconded by Dr. H. C. Watts. The Chairman stated that in view of the deficit of £138 13s. 8d. shown in the accounts, the Council had decided as a measure of economy that the meetings of the next session should be held in the library instead of at the Royal Society of Arts as heretofore, and that efforts were also being made to obtain financial assistance. The Council were fully cognisant of the difficulties arising from continued annual deficits, and were doing their utmost to make the Society's income cover the expenditure.

The Council's proposal to delete from Rule 6 the words "of the Fellows and Associate Fellows and one-half of the other members," was carried; an amendment by Dr. Watts and Mr. Walsh to substitute "one-third" for "one-half" at the beginning of the rule being withdrawn.

The Council's proposal to add, at the end of Rule 6, the words "provided that a retiring member who has failed to attend a minimum of three meetings of the Council during the year shall not be eligible for re-election for the subsequent year unless he has received leave of absence by a resolution of the Council duly recorded in the minutes" was withdrawn after discussion of an amendment to delete these words moved by Dr. Watts, seconded by Mr. F. P. Walsh and supported by Colonel Moore-Brabazon.

Rule 6, as amended by the meeting, was therefore declared to read as follows:—"One-half of the Council shall retire annually; the members who shall retire shall be those longest in office, and in the event of equal length of time, the members to retire shall be decided by ballot of the members of the existing Council. Retiring members shall be eligible for re-election if re-nominated."

The scrutineers then presented the results of the ballot, and the following members were declared duly elected to serve on the Council for the two years ending March, 1926:—Mr. Griffith Brewer, Major-General Sir W. S. Brancker, K.C.B., A.F.C., Professor C. Frewen Jenkin, C.B.E., Major A. R. Low, Mr. W. O. Manning, Mr. J. D. North, Lieutenant-Colonel A. Ogilvie, C.B.E., Sir Napier Shaw, F.R.S., Major H. E. Wimperis, and Mr. R. McKinnon Wood.

The scrutineers were thanked for their services and the meeting closed with a vote of thanks to the Chairman.

PROCEEDINGS

SIXTH MEETING, 59TH SESSION

A meeting of the Society was held at the Royal Society of Arts, John Street, Adelphi, London, on Thursday, January 10th, 1924. Colonel A. Ogilvie (Chairman of the Society) presided.

The following papers were read:—"Some Materials in Aircraft Construction," by Mr. John D. North, F.R.Ae.S. "Materials in Aircraft Construction," by Dr. Leslie Aitchison, D.Met., B.Sc., F.I.C.

SOME MATERIALS IN AIRCRAFT CONSTRUCTION

BY JOHN D. NORTH, F.R.AE.S.

There are various considerations which govern the use of materials in engineering construction. The use of many of them is founded on precedent, and in the case of the older branches of engineering the original reason for their use is sometimes obscured.

From time to time as new classes of materials are developed they are gradually incorporated, often breaking their way with difficulty through the wall of prejudice with which engineering caution so often surrounds its designs.

In spite of its recent origin and rapid growth the aeroplane is no exception to the general course of engineering development. It has, however, been profoundly influenced by the exceptional circumstances of its forced growth, under war conditions, which has left its mark perhaps more on the materials of construction than on any other general feature of the aeroplane.

When the first efforts at flight were made the limited resources of the experimenter made it necessary for him to choose his material among those which could be obtained comparatively easily in the ordinary commercial world.

The result was the aeroplane of wood, wire and canvas, the type of construction used in all the machines on which flight was first achieved.

In the second stage of the early development aluminium castings were extensively introduced, and these castings as a strut attachment, together with eyebolts and "U" bolts for fixing the tension wires, came into general use.

Shortly after autogenously-welded mild-steel fittings commenced to make their appearance, and the use of this joining process and the limitations of the materials on which it could be successfully carried out are to a large extent responsible for the extensive use of plain low carbon sheets and tubes, which obtains even to-day.

On the subject of the wood used in aeroplanes I need say little. In spite of the early popularity of ash and the occasional structural use of such materials as Honduras mahogany, lancewood and a few others, it was soon appreciated that silver spruce possessed mechanical properties which among timbers rendered it uniquely suitable for light construction.

The supplies of this timber most suitable for aircraft work became virtually exhausted during the war, and all efforts have failed to supply a substitute which approaches even closely to it as a light constructional material.

An immediate increase of the valuable supplies of silver spruce is hardly within the capacity of man, and since it has been found that metal can with advantage be used in the place of first quality silver spruce and *a fortiori* in place of its inferior substitutes, I propose to discuss metals only in these notes.

The problem of structural design in aeroplanes possesses many unique features which are not to be found among those of ordinary engineering structures. By this I do not mean to say that the fundamental theory of structure is in any way modified in its application to aircraft, but rather that the peculiar conditions to be fulfilled bring into prominence various points which, in ordinary civil engineering, are so readily smoothed over as practically to escape notice. I need scarcely remind anyone here that in no other form of structure does weight economy so amply repay the engineer. It is true that in certain cases, such as crane jibs, the importance of light structure is recognised, but no designer of hoisting machinery has thought fit to go to the lengths which are accepted as ordinary aeroplane practice in order to obtain lightness.

Just as weight economy reimburses the aeroplane designer, so there is a heavy penalty for faliure to achieve a light structure. The useful load capacity of the aeroplane is within such a narrow margin of the gross weight that the intrinsically heavy aeroplane is always at a grave disadvantage. Commander Hunsaker suggested, in his Wilbur Wright Memorial Lecture before the Royal Aeronautical Society, that the preliminary weight estimate of an aeroplane should be regarded as a bank account which under no circumstances must be overdrawn. This is a precept which I would heartily endorse; but the practice is scarcely easier structurally than it is financially.

Weight breeds weight; and it is no uncommon event for a completed aeroplane to be as much as five per cent. in excess of its estimated gross weight, and the structure has to be strengthened to withstand the extra load; thus more weight is added, and so the pernicious cycle continues.

In order to solve the problem of design of light structural members for the aeroplane we must utilise the following means of approach:—Firstly, we must know the external forces on the aeroplane which have to be withstood; secondly, we must find the loads in the various members produced by these forces; thirdly, we must devise forms and select materials for these members in order that they may perform their duty with a minimum weight expenditure. This form of approach rather suggests that the arrangement of the various members is predetermined, and while this is not actually true, we do not approach the problem of structural design with an absolutely open mind as to the general arrangement of the machine. As in all creative engineering work, the arrangement adopted by the designer is chosen to meet, in his general opinion, the various requirements of the finished aeroplane. The vast number of variables renders impossible a complete analytical attack on the problem of the general arrangement, and it is for this reason that theoretical structural knowledge is no substitute for experience. As every engineer knows, he can, within the limits of his experience, intuitively appreciate the various points which arise in preliminary design, and the analytical method is applied at a later stage to verify his intuition and to extract the last ounce which is to be saved by refinement of design. It is the importance of this ounce that gives such an impetus to the analysis of structural problems in aircraft design and the development of new materials, and ways and means have been evolved which are unnecessary in general engineering practice, where they give no adequate return for the labour involved.

Since, from a structural point of view, the special quality of the aeroplane is its lightness, it would appear obvious that those materials would make the greatest appeal to the aeronautical engineer which will result in the lightest structure, but an examination of the modern aeroplane shows a general use of materials which do not satisfy this requirement.

To a very large extent I believe this to be due to the precedents of pre-war practice, which under war conditions crystallised into standards, on which the efforts of manufacturers could most conveniently be concentrated.

In a previous paper* before the Society I discussed some of the methods whereby very substantial saving could be effected in the structure weight of an aeroplane. By the use of proper materials in *all* parts of the aeroplane this saving could be considerably augmented. We have to consider whether, in adopting these new materials and methods of manufacture, we are on sound metallurgical grounds, a point which is dealt with by Dr. Aitchison in the other part of this paper; secondly we must consider how manufacturing costs will be affected.

I feel that this latter aspect of the case has not been viewed in the proper light. It is I think generally admitted that our present experience has shown us that this saving of weight can be realised, but I do not feel that its full significance is understood.

Let us examine as an example a case of a high-performance medium-range day-bomber, one of the most important classes of offensive aircraft. A machine of this class should be able to protect itself by reason of its performance and manœuvring powers against defensive attack from enemy aircraft without the assistance of an escort. The performance necessary can only be realised with a power loading of about 10 lbs. per horse-power, and fuel must be carried for four hours' flight at full speed at ground level.

Supposing a fair representative value for the structure weight of the "standard construction" aeroplane of this class to be 36 per cent. An examination of figures for aeroplanes made of wood, mild steel and so on convinces me that this is a reasonable figure for aeroplanes between 7,000 lbs. and 12,000 lbs. gross weight of this type of manufacture. The 10 lbs. carried by each horse-power will then be made up as follows:—

Engine	2 lbs.
Fuel	2 lbs.
Engine installation, *i.e.*, tanks, propeller, exhaust pipes, fuel pipes, water system, etc., of standard type	1 lb.
Structure	3.6 lbs.
Military load	1.4 lbs.
Total	10 lbs.

The military load is thus 14 per cent. of the gross weight of the aeroplane. By introducing light alloys into the fuel system by special construction of tanks and so on, it should be possible to reduce the item for installation to 0.8 lbs. We can already with confidence say that the use of high-tensile steels and light alloys will reduce the structure item to 2.7 lbs. The balance will now be as follows:—

Engine	2 lbs.
Fuel	2 lbs.
Installation	0.8 lbs.
Structure	2.7 lbs.
Military load	2.5 lbs.
Total	10 lbs.

The military load is now 25 per cent. of the gross weight. Suppose that the military load is required to be 2,000 lbs., the weights of the two aeroplanes to fulfil

* "The Case for Metal Construction," AERONAUTICAL JOURNAL, January, 1923.

precisely the same functions so far as performance, range, and carrying capacity are concerned will be roughtly 14,000 lbs. and 8,000 lbs. respectively. They may be appropriately pictured as, in the first case, a biplane 80ft. span with two Rolls-Royce Condor engines, and in the second case a biplane 60ft. span with two Bristol Jupiters.

To consider first the question of prime cost, a very fair figure for the cost of aeroplanes of standard construction is 15/- per lb. of gross weight, not including the cost of engine or military equipment, instruments, etc., while a reasonable average figure for the cost of aeroplane engines is £4 per horse-power. The cost of the first aeroplane as influenced by gross weight, *i.e.*, excluding cost of equipment, will therefore be as follows :—

	£	s.	d.
Engine, one h.p.	4	0	0
Aeroplane, 10 lbs. at 15/- per lb.	7	10	0
Total cost per h.p.	11	10	0
Gross h.p. 1,400, gross cost	16,000	0	0

I have used round numbers in the arithmetic, but have everywhere under-estimated rather than over-estimated the cost by so doing.

Now let us turn to the second machine. The 800 h.p. at £4 per h.p. will cost £3,200, and deducting this from the £16,000 (the gross cost of the first machine) we are left with £12,800 for the aeroplane structure, representing a figure of £1 12s. per lb. of gross weight of the aeroplane. That is to say, the cost per lb. of gross weight can be *more than doubled* without making the prime cost of the aeroplane to fulfil a specific duty any higher than it would be for the standard construction. Manufactured in moderate quantities, the difference in cost per unit weight is nothing like as great as this, and there is no doubt whatever that the lighter type will be very much cheaper in prime cost. The effective working of the materials necessary to achieve this light structure requires a more elaborate engineering organisation, more extensive and more expensive plant, and also a considerable amount of tool-making, die-sinking for drop stampings, etc., all of which are in the nature of a fixed standing charge of constant amount very nearly independent of output and consequently a rapidly diminishing percentage oncost as the output for a given type increases.

The advantage does not, however, end with prime cost. The cost of engine maintenance where 400 h.p. engines are used instead of 700 h.p. is greatly diminished, while the larger aeroplane has a fuel bill 75 per cent. greater than the smaller. Handling, shed accommodation, transport are all simplified, and a very large saving in operating cost *for the same service* is indicated.

From a military point of view there is the further tremendous advantage of greater manœuvrability in favour of the smaller machine. With constant-ratio of control force to hinge moment, *i.e.*, with similar balancing, the relative time taken by two similar machines of different size to execute a given manœuvre varies as the square of their linear dimensions. In other words, the time taken by the larger machine to execute a manœuvre will be 75 per cent. greater than in the case of the smaller machine. This difference of manœuvrability is so great that in all probability the larger machine could no longer be considered to come within the class of self-defending aircraft. It will, of course, be noticed that the magnitude of the advantage in favour of light construction is emphasised by the large proportion of the permissible weight per horse-power represented by the engine, fuel and installation. The constant efforts to increase performance and range in military aircraft are likely to increase this figure in the future rather than to reduce it. It is thus evident that even apart from the saving in prime cost and running cost an air force equipped with aeroplanes of the heavier type of construction is likely to be at a hopeless military disadvantage against a force armed with the lighter type of machine.

In the case of commercial aircraft, where the power loading rises to 15 or 16 lbs. per h.p. the advantage of the lighter type of construction is, of course, not so startling. It will probably be correct to say that the prime cost for a given service would be about the same in both cases, the advantage being gained in reduced running expenses.

Similar arguments can of course be applied to the design of equipment. On the type of military aeroplane which has just been considered the prime cost of aeroplane and engine of " standard construction " is £8 per lb. weight of military load. Therefore every ounce saved in equipment means a saving of 10/- worth of aeroplane, which has not only to be bought but maintained.

With the lighter type of aeroplane construction this saving will probably represent about 6/- or 7/- an ounce. An examination of standard military equipment is sufficient evidence that this point of view is not appreciated by those responsible.

If I have demonstrated that it is worth while using the best possible materials to give the lightest structure, I can now turn to consider what these materials are. The principal structural parts of an aeroplane may be grouped under the heading of ties and laterally-loaded struts. I have already discussed in a previous paper* the methods of construction and the materials, by the use of which these members may be made as light as possible. In order to find a basis for the discussion of the physical properties of materials suitable for these members we must remember that an aeroplane is primarily designed on the failure strength of its members. Although an aeroplane is a redundant structure, the standard method enforced for calculating the loads in the members ignores many redundances, and calculations, except in very special cases, are based solely on the maximum load the member is capable of taking. Where redundances exist the straining of members beyond the limits of proportionality, which may occur at moderate loads (*e.g.*, flexure of struts) gives a distribution of loads throughout the structure, which is distinctly removed from that which would be calculated by the usual " strain energy " method, and in most cases this straining has the effect of distributing the loads in a more favourable manner. The increase in real strength of the aeroplane on this account is considered in specifying the load factors.

Ties

Within the limits described above the only property of ties from the point of view of static strength which need be considered is the ultimate tensile strength. The ratio of elastic limit to ultimate must, of course, be such that with the load factors used, the members are not liable to be permanently deformed under ordinary service conditions. The ultimate tensile strength of materials will be referred to in the rest of these notes as F_t.

Laterally-Loaded Struts

The determining property of the material is the value of E, and of E_t (the slope of the stress-strain diagram) at the failing stress on the compression stress-strain curve. This is based on the assumption that as strain is released the stress falls according to the value of E. This has been found to be true for many materials, but it may not be strictly so for all, in which case two values of E_t (on the upward curve, and on the downward curve) for the stress in question are required. Yield point, in materials which possess it, is the point of failure for a considerable range of lengths of any given strut, but this is really a particular case of the general result.

* Ibid.

An attempt has been made to define the critical stress in compression, as the stress at which some definite small plastic extension takes place, in which case it has been called the proof stress. It is very doubtful if this method is accurate, and for the purposes of these notes I shall refer to the critical compressive stress as F_c.

Apart from possessing properties favourable to these strength requirements, materials must be able to be worked commercially, and they must have adequate ductility to avoid the formation of stress cracks, and similar failures due to the inability of the material to adapt itself to highly-concentrated local stress. A fairly wide range of steels meets these conditions in varying degrees, and it is possible that there is a wide range of light alloys which will also satisfy our requirements, but experience in this latter direction is limited to one or two well-known alloys.

TABLE I.

	Bar.	Sheet & strip.	Tube.
Low carbon		S.3	T.6 T.22
Medium carbon	S.1		T.2 T.5
Medium tensile alloy	S.2	S.43	
High tensile alloy		S.40	
Very high tensile alloy			T.2

Steels

Table I. shows the various classes of steel with different conditions of manufacture, which are in use or are specially suitable for aeroplane construction. Where B.E.S.A. specifications exist they have been indicated. The low carbon group in the normalised state only gives F_c 18 tons per sq. in. and F_t 26 tons per sq. in. These can be brought up to F_c 28 and F_t 32 by cold work. The very low specific strength of these materials makes them uneconomical structurally.

The medium carbon group in the normalised state will give an F_t of about 35 tons per sq. in., and when cold-worked an F_c of 35 to 40 tons per sq. in. In this latter state they are merging into the medium tensile alloy steel group with F_c 40 to 50 tons per sq. in., F_t 50 to 55 tons per sq. in. As the alloy steels are brought up to strength by hardening and tempering, and not by cold work, they are obviously more suitable for working up into plate fittings. Experience has shown that medium tensile alloy steels with an F_t of about 50 tons per sq. in. are very suitable for making fittings and represent a saving of nearly 50 per cent. in weight on the normalised low carbon sheets. Alloy steel bar with an F_t of 55 tons per sq. in. is similarly an economical substitute for medium carbon bar, the extra difficulty of machining this class of material being to a large extent compensated for by the smaller amount of material which has to be removed. These two materials seem to represent an excellent compromise between ductility and strength, and it is scarcely practicable to use steels for fittings with a higher tensile strength; in fact, a slight reduction, say, 10 per cent., in the value of F_t of S.2 will be advantageous if a definite gain in machining qualities is to be expected. The high tensile alloy steel, F_c 65 to 75 tons per sq. in., F_t about 80 tons per sq. in., can only be worked satisfactorily in very thin material, *e.g.*, under 22 G. on account of its low ductility. It is probable also that the very thin material is not liable to stress cracks owing to its elastic instability, causing the material to buckle rather than crack. There is a distinct use for solid-drawn tubes having these mechanical properties, and such a material can be obtained by tempering down the very high tensile alloy steel tubing T.2, which is commonly

used for axles. In addition to the above, medium carbon steel rods are rolled or swaged into Raf wires and tie-rods, a very large amount of cold work put into the material bringing the F_t up to 75-80 tons per sq. in.

Fairly frequent fatigue failures in Raf-wires in service naturally makes the material worthy of special consideration, but owing to the manufacturing difficulties involved, I believe that no more favourable proposition has been put forward.

Joining Processes

The use of alloy steel sheets for built-up fittings immediately raises the question of joining processes. Autogenous welding is, of course, excluded by the nature of the material, and I understand that the metallurgist considers this to be good riddance to bad rubbish. Brazing, particularly dip-brazing, is attractive, since it can be incorporated in the heat-treatment programme, but personal experience of the formation of cracks (whether due to stress or inter-crystalline penetration seems uncertain) have made me very cautious of using this process for alloy steels. Certain precautions have been suggested for carrying out the process, and these seem to have led to satisfactory results, though, naturally, satisfactory results are of a negative nature, and require to be very extensive to be convincing. In the meantime riveting and sweating have been utilised successfully and found to meet every requirement. The function of the sweating is primarily to relieve riveting or pinning at joints from fluctuating stress, though one would imagine that as a joining process sweating alone, when properly carried out, is at least as reliable as glue in wood-joining.

The use of high tensile steel bar for bolts and nuts requires a reconsideration of the range of sizes which are to be used. Steps of 1/16in. in diameter are too coarse, and as—thanks to the initiative of the Royal Aircraft Factory—the aircraft industry was many years ago robbed of the international standard metric system, we are compelled to fall back on the British standard fine thread in stages of 1/32in., and on the bastard offspring of the British Association for sizes under 7/32in.

Light Alloys

Duralumin, the best known of the light alloys, gives an F_c of about 15 tons per sq. in., and an F_t of 25 tons per sq. in. Specifically, its strength is of the same order as the medium tensile alloy steels, and it may be usefully considered as a convenient substitute for very thin steel sheet avoiding the difficulties of instability, etc., which would be found with a material less than 0.01in. thick. 20 G. duralumin sheet is roughly equivalent to 30 G. steel sheet. Duralumin is particularly suitable for torsion tubes in control surfaces where the question of rigidity makes it necessary to use the large diameters, while the very low stress would bring the appropriate thicknesses of steel into the region where failure by buckling takes place at a low load. Duralumin may also be used with advantage to form an extension on the lower scale of bolt sizes, particularly for joining duralumin to duralumin and for equipment installation.

Drop Stampings

With the use of high-grade materials drop stampings for joints must be available to the designer. Only in a very few cases is it possible to make a reasonably light joint with a steel stamping unless it is practicable to machine it all over; these are the cases where the surplus material necessary for the purposes of draw can be removed. I recall vividly the manufacture of the frame joints of the R.E.7 aeroplane, where, owing to the designer of the joints having failed

to consider this fact, the joints came out greatly in excess of their estimated weight, and large numbers of gunsmiths had to be employed to chip off the surplus material. With light alloy stampings, owing to the greater finished thickness of the part, the difficulty of the draw is not so acute, and I think that stampings of this material will in the future play an important part in aircraft construction. The fine dimensions of the finished part in any material, however, make it necessary for the greatest care to be taken to register the dies accurately and to maintain a uniform thickness of flash.

Engine Installation

The extensive use of copper and brass in the fuel system, and of tinned mild steel sheet in tanks, offers great opportunity for weight economy by the substitution of better materials. The general introduction of duralumin for cocks, connections and duralumin or aluminium for the pipes in the water, fuel and oil systems seems inevitable. Tinned mild steel sheet for tanks might with advantage be replaced by stainless iron or a nickel-copper alloy such as Monel or Corronil metal with improvement from a strength and weight point of view, and the reduction, if not elimination, of the constant corrosion troubles due to the difficulty of getting away chlorides from the soldering fluxes. Aluminium or light alloy tanks depend for their success on a petrol-tight joining process—a problem which cannot be considered to have been wholly solved.

Exhaust pipes, the thickness of which is largely governed by the question of scaling, can be made of thinner material if stainless iron, Monel or Corronil metal, or some other metal which does not oxidise readily at high temperatures, is employed. Such manifolds, experience has shown me, are very satisfactory.

Conclusion

Objection has been raised by certain people to the use of high-quality materials on the grounds that they will be abused by those who are charged with the maintenance of the aeroplane on service. This I believe to be a most improper way to regard an engineering matter. There is nothing whatever in the use of such materials which will prevent the skilled artisan, the semi-skilled workman or the labourer from carrying out their ordinary duties of maintenance satisfactorily provided they are under proper engineering supervision. An engineering training cannot be acquired as part of a two years' college course, and the work of the maintenance engineer is essentially a whole-time job. I do not believe that any attempt to run a large flying organisation, either service or civil, can be really successful unless the engineering work of maintenance is carried out directly under the supervision of professional engineers. I do not advocate the use of hundred-ton steels or excessively-cold-worked ultra-light alloys, but rather materials which by their nature are best in consideration of strength, lightness and reliability, and which by their fundamental properties can be so treated that they reach down to our requirements rather than materials of inferior quality which must strain up to them.

MATERIALS IN AIRCRAFT CONSTRUCTION

BY LESLIE AITCHISON, D.MET., B.SC., F.I.C.

The problems connected with the material used in the construction of aircraft are very numerous, and the time available in one lecture is far too short to consider them in any kind of detail. It seems to be more appropriate to approach the matter broadly and to consider some of the basic problems with a little thoroughness than to examine a number of details in a superficial manner. The main objection that can be urged against this method is that the conclusions reached are by no means confined in their application to aircraft materials, but apply almost equally to most of the arts in which the same or similar materials are employed. After all, the aeronautical engineer is mostly concerned to obtain the ideal sample of any chosen material. This is due firstly to the fact that he subjects the materials to a higher duty, and secondly (what is really only a corollary to the first cause) he leaves a much smaller margin to cover what is known sometimes as the factor of ignorance and sometimes as the factor of unreliability, but what is (however named) the factor which represents the degree to which the material actually employed differs from the ideal sample of the material. The smallness of this allowance—the margin of manufacturing error—which is the distinguishing mark of aeronautical construction (as viewed by the metallurgist) is really a most important matter. The problem of aeronautical materials becomes in fact very largely the problem of how to minimise the dangers that arise from the narrowness of the margin permitted between the "ideal" and the average "real."

It must be said at once that only the metallic materials of aircraft construction are contemplated herein. These materials mainly comprise the following items:—

(*a*) Mild steel in the sheet form.
(*b*) Medium carbon steel—as cold drawn or hot rolled in bars—and as drop forgings.
(*c*) Strip steel of varying tensile strengths.
(*d*) Medium high tensile steel as sheet and bar.
(*e*) High tensile cold-worked bars, rods and wires.
(*f*) Duralumin as sheet, strip and forgings.
(*g*) Aluminium as sheet and strip.
(*h*) Steel, aluminium, and duralumin tubes of various maximum stresses.
(*i*) Light alloy castings.

How can all these various materials be considered together, *i.e.*, as mere examples of one and the same problem? The only way is to find out what are the most common properties that are expected to be present in one and all. These would appear to be only strength and lightness, or what may be called generally specific strength, *i.e.*, the strength per unit mass. The plain consideration therefore becomes that of the properties that really constitute the strength of the materials as they are used. The best way in which the strength can be considered is to examine those properties that contribute towards strength and then to see in what ways and to what extent these properties are affected by the other qualities of the materials—as manufactured, and as treated by the aero constructor. In the course of this examination it may well be found that the apparent paradox that "the stronger the material the weaker the part" is largely true.

Considering the metallic materials quite generally, it is fairly evident that the aero constructor views strength in various ways, and in fact utilises various

mechanical properties of metals as criteria of the strength of different parts. At different times he appears to require the maximum stress, the elastic limit, the proof stress, the yield point, or the fatigue strength of the metal. With all these properties he yet calls for an accompaniment of a high ductility and as great a toughness as possible. The reason for these last requirements will be considered later. At the same time the constructor is interested in the value of the Young's Modulus of the materials.

It may be of some advantage to devote a little space to these different properties in turn. The first to call for attention is the *maximum stress*. The values generally found in typical samples of the materials given above, supplied in accordance with B.E.S.A. specifications, are given in Table I. Side by side are quoted the strength/density ratios of the materials, these of necessity providing a sounder basis of comparison for many purposes than the strength/area ratios usually quoted.

TABLE I.

Material.	Max. stress tons/sq. in.	Max. stress/ density.
Mild steel sheet	26	3·30
Medium carbon steel bar or forgings ...	36	4.60
Cold-drawn steel bar	36	4.60
Medium tensile steel strip	52	6.62
High tensile steel strip	76	9.70
Medium tensile steel bar	55	7.0
High tensile cold-worked steel rods or wire	78	10.0
Duralumin	27	9.6
Aluminium	10	3.67
Soft aluminium	6	2.22
Light alloy castings	10	3.40

The figures in the table call for little comment, showing as they do a range of maximum stress from 6 to 78 tons and a strength/density ratio between 2.2 and 10.0. It may be asked quite legitimately why the maximum stresses for each material are limited in the way indicated by these figures. This question very often receives its best answer on practical grounds, though it must be admitted that in some instances the practical reasons are prejudices sanctified by prolonged observance and that they cease to be good reasons when examined impartially.

TABLE II.

Hardening Temp. °C.	Tempering Temp. °C.	Max. stress tons/sq. in.	Elongation per cent.	Red. area per cent.	Impact foot lb.
830	—	114	13	28	12
830	300	96	13	40	5
830	400	83	14	47	7
830	500	73	17	52	35
830	600	63	21	59	55
830	650	59	23	63	67
830	700	71	13	40	29

Even so, there is some quite reasonable ground for the particular values of maximum stress that are quoted, and in quite general terms it may be said that the values chosen are those that with a given metal are accompanied by the most satisfactory ductility and toughness. This statement applies perhaps more particularly to steels than to the other materials, but is true of all metals in a greater or less degree. To indicate this briefly the test records given in Table II. and Fig. 1 for a typical steel may be referred to. These tests clearly show that at a

certain maximum stress, *i.e.*, 59 tons, the ductility and toughness of the steel are at a maximum. With this particular steel, then, the *most suitable* maximum stress is clearly 59 tons/sq. in. The same kind of information could be shown for other steels, which leads to the definite conclusion that for any particular steel the best condition is produced by such and such a heat treatment, which in

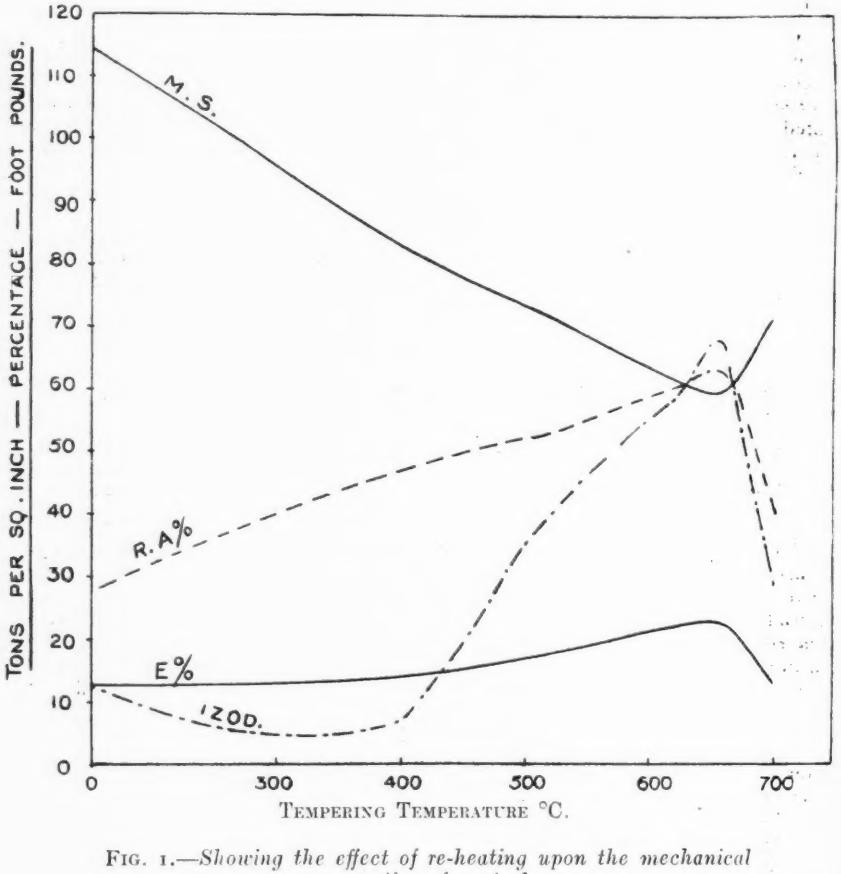

FIG. 1.—*Showing the effect of re-heating upon the mechanical properties of a steel.*

turn fairly definitely fixes the maximum stress (and incidentally the concomitant ductility and toughness. Conversely it can be said that for any particular desired maximum stress there is a particular steel, heat treated in a particular way, that gives this maximum stress most suitably. The variation in the other properties of a number of different steels, all heat treated to give the same maximum stress, are shown in Table III., where the superiority of one particular steel as regards ductility and toughness is manifest. It is a sound rule to work upon that an alteration in maximum stress is better obtained by the use of a different material than by an alteration in the treatment of the same material, for the same material cannot very well have two best conditions.

TABLE III.

Heat treatment of steels (all different).	Max. stress tons/sq. in.	El'gation per cent.	Impact foot lb.
Air-hardened 820°C., tempered 500°C.	76	16	32
Air-hardened 820°C., not tempered	73	14	7
Oil-hardened 850°C., tempered 400°C.	77	17	14
Water-hardened 850°C., tempered 400°C. ...	75	14	11
Water-hardened 870°C., not tempered	77	10	3
Water-hardened 860°C., tempered 500°C. ...	74	16	10

The same considerations apply to the light alloys, however they are hardened. At a certain value of maximum stress the best values of ductility are obtained by using a certain material in a certain way. The range of combinations is not so wide as with steel, but a fairly large variation may be induced by differences in the amount of working. This process should be very carefully and strictly controlled, as otherwise maximum stress will be obtained at the expense of other equally valuable properties.

Whilst dealing with maximum stress it may be pointed out briefly that hardened and tempered steels are the most suitable to give useful values of this property. Higher values of the maximum stress of any material are usually produced by hardening, either by quenching or by cold working, and both these processes reduce the ductility and toughness. Consequently the brittleness of

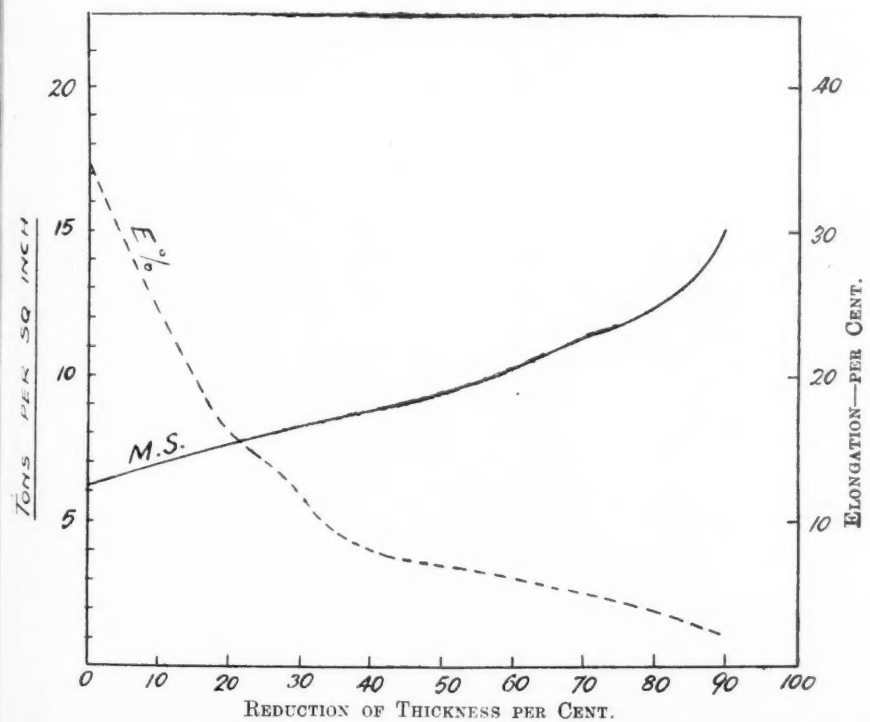

FIG. 2.—*Showing the effect of different amounts of cold work upon the mechanical properties of a metal.*

quenched steel should be reduced by tempering—at the highest convenient temperature—whilst the brittleness of the worked materials should be reduced by limiting the amount of work-hardening as much as possible and by subsequent blueing. The effect of varying amounts of cold work upon both the strength and the ductility of a typical material can be seen in the values shown in Table IV. and the curves in Fig. 2.

TABLE IV. (Aluminium Sheet).

Reduction of thickness per cent.	Max. stress tons/sq. in.	Elongation per cent.
—	[illegible]2	35
10	[illegible].9	25
20	7.5	16
30	[illegible]	12
40		8
50	[illegible]	7
60	[illegible]	6
70	11.5	5
80	12.4	4
90	15.0	2

The *elastic limit* of metals is a very variable proportion of the maximum stress. For the typical materials quoted above the values of this property are shown in Table V., together with the ratio between the elastic limit and the density, and also that between the elastic limit and the maximum stress. The variations are obvious both in the absolute values and the ratios.

TABLE V.

Material.	Elastic limit tons/sq. in.	Elastic limit / max. stress.	Elastic limit / density.
Mild steel sheet	13	.50	1.65
Medium carbon steel	18	.50	2.30
Cold-drawn steel	27	.75	3.35
Medium tensile steel strip ...	35	.67	4.45
High tensile steel strip	50	.66	6.4
Medium tensile steel bar	35	.64	4.45
High tensile cold-worked steel ...	25	.32	3.20
Duralumin	15	.58	5.30
Aluminium	7.5	.75	2.77
Soft aluminium	2.5	.42	0.93
Light alloy castings	4.0	.40	1.38

It is to be remembered that hardening a metal, either by quenching or the application of cold work, generally reduces the ratio between the elastic limit and the maximum stress, and that this ratio can be recovered and often actually increased by subsequent reheating. All steels that have been hardened should therefore be reheated to temperatures of at least 350°C. The quenched steels should be tempered at higher temperatures than this for other reasons (ductility and toughness), but if the work-hardened steels are heated beyond 450°C. they lose the strength imparted by cold working.

After quenching and tempering, or work hardening and blueing, the ratio of elastic limit to maximum stress of all metals is markedly higher than in the same metals when normalised. The same thing applies to the light alloys when cold worked and reheated to relatively low temperatures. This can be appreciated from a reference to Table VI.

XUM

TABLE VI.

Condition.	Elastic limit tons/sq. in.	Elastic limit max. stress.
Normalised	22	·55
Worked not blued	24	·39
Worked blued 100°C.	32	·55
,, ,, 200°C.	38	·67
,, ,, 300°C.	45	·75
,, ,, 400°C.	42	·72
,, ,, 500°C.	37	·71
,, ,, 600°C.	28	·70

The *proof stress* of metals is not without its controversial aspect. In these present remarks it may be as well, therefore, to say that the property is taken to be the stress that produces 0.1 per cent. strain greater than the elastic strain produced by the same stress, assuming that E is the same at this stress as at stresses inferior to the elastic limit. The variations in the value of this property can be seen from Table VII., in which are shown not only the proof stress but the proof stress/density ratios and the proof/stress maximum stress ratios of various typical metals.

TABLE VII.

Material.	Proof stress tons/sq. in.	Proof stress max. stress.	Proof stress density.
Mild steel sheet	16	·62	2·05
Medium carbon steel	22	·62	2·80
Cold-drawn steel	30	·83	3·82
Medium tensile steel strip ...	42	·80	5·35
High tensile steel strip	57	·76	7·3
Medium tensile steel bar	40	·73	5·1
High tensile cold-worked steel ...	40	·52	5·1
Duralumin	16·5	·62	5·9
Aluminium	8	·80	2·95
Soft aluminium	3	·50	1·11
Light alloy castings	5	·50	1·73

Substantially it may be said that the rules that apply to the elastic limit apply equally to the proof stress, though perhaps not in quite the same degree. Nevertheless, it is of importance to appreciate that the reheating of hardened materials is necessary in order to induce the highest ratio of proof stress to maximum stress.

A further point of the same kind is to be noticed in regard to the ways in which the other properties may vary in two materials having the same proof stress. In Table VIII. are shown the complete tensile properties of two steels having substantially the same proof stress. These are decidedly different. The difference is just as great and perhaps more obvious in the stress/strain curves of the two materials as set out in Fig. 3.

TABLE VIII.

	Steel A quenched & tempered.	Steel B worked & blued.
Proof stress tons/sq. in.	64.5	62.9
Elastic limit tons/sq. in. ...	24.1	41.9
Max. stress tons/sq. in.	110.5	63.8
Elongation per cent.	12.0	11.5
Red. of area per cent.	28.0	27.3

If they show nothing else, the values in Table VIII. and the curves in Fig. 3 indicate plainly that the quotation of the proof stress is by no means an exhaustive definition or a precise statement of the mechanical properties of a metal.

So much has already been said about the *fatigue strength* of metals, and so much more is likely to be said before the process of fatigue is wholly defined and understood, that no useful purpose would be served by discussing the property as a property. It must be sufficient to quote the actual values that have been obtained upon various metals.

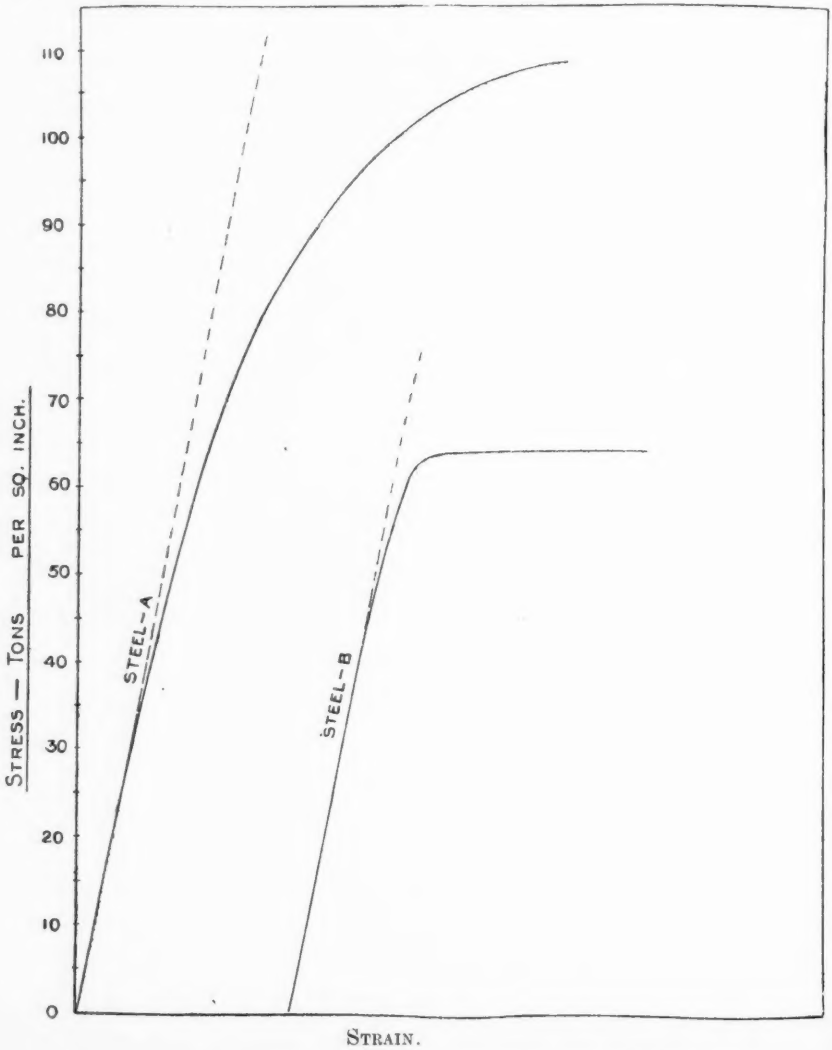

FIG. 3.—*Showing the stress/strain curves of two different steels of the same proof stress.*

These values all represent one set of conditions, *i.e.*, equal plus and minus stresses, and a representative set of such values are given in Table IX.

TABLE IX.

Material.	Fat. range tons/sq. in.	Fat. range max. stress × 2	Fat. range density.
High tensile alloy steel	±41	·50	10.4
Medium tensile alloy steel ...	±28	·50	7·1
Medium carbon steel	±17	·45	4·3
Cold-worked steel	±16	·42	4·1
Mild steel	±12.4	·42	3·1
Duralumin	±10.5	·41	7·44
Light alloy castings	± 3.0	·30	1.94

In the same table are given the ratios of fatigue range to the maximum stress and also the ratios of the fatigue range to the density of the various metals referred to.

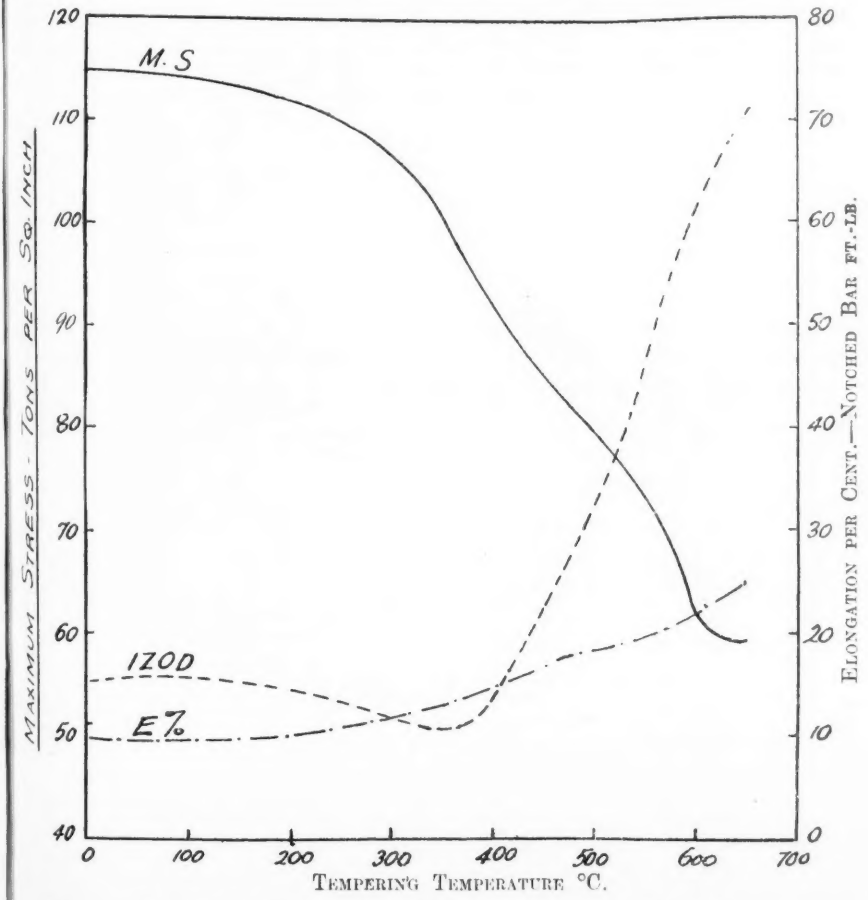

FIG 4.—*Showing the change of ductility and toughness produced by tempering.*

One of the singular things about the fatigue strengths of metals is their almost complete independence of all the other mechanical properties of the materials. It seems to be established fairly definitely that the highest ratio of fatigue range to maximum stress is found in the metals having the lowest maximum stress. It is certain that this ratio is lower in hardened metals than in the same metals after the hardness is reduced. (This really refers chiefly to steel and iron. Soft iron gives the highest ratio in this class of metal. The variations with other metals are not so easy to demonstrate.)

Time is not available for an investigation of the way in which the fatigue range of a metal is affected by variations in the relative magnitudes of the component stresses of the range, but it is not wise to omit all reference to the fact that the fatigue range of a metal (even under equal plus and minus stresses) is affected greatly by its condition. Cast metal gives a much lower value than the same metal when forged. Also a steel that is tested so that the fatigue stresses are applied parallel to the grain of the metal has a higher fatigue range than the same metal tested so that the stresses are imposed at right angles to the fibres.

The very notable variations in the actual values of the fatigue ranges of materials under different conditions makes it very necessary that a conservative estimate should be made of the resistance of any metal to fatigue stresses. They also indicate the need of intense caution in accepting any particular margin of safety that is based upon an assumed value of the fatigue range, which may only be correct for one set of conditions.

Without claiming too much accuracy for the generalisation, it may be suggested that in the steels used in aircraft it would be reasonable to take ± 40 per cent. of the maximum stress as representative of the fatigue range in " longitudinal " specimens and about ± 30 per cent. in " transverse " specimens. For light alloys both of these values ought to be reduced by about one-third. Doubtless there are many, if not a majority of, instances in which it is scarcely possible to diagnose the condition of a particular part and to say that the stresses (in so far as they are fatigue) are applied in the longitudinal or the transverse direction exclusively. In most instances it would appear wisest therefore to assume that the transverse conditions hold, and to calculate the factors of strength accordingly.

The values given above are of course those obtained in tension and compression. The torsion values are less than the tension, but generally appear to be less by a definite proportion, being usually round about 60 per cent. of the tension values in so far as they have been determined.

By means of such figures and considerations as those given above, it seems likely that the strength values of the various aircraft materials may be regarded as well covered. The values given, however, are more or less the " ideal " values, and the " real " ones may be quite appreciably different from the " ideal." What amounts to much the same thing in the end, though it is scarcely the same thing in appearance, is that in very many instances these ideal values, even though present in the materials, are not realised in practice. The " real " values are apparently much below the " ideal."

The general reason for this discrepancy may be stated briefly to be found in the local imperfections of the metal. This diagnosis is certainly bound to appear as an anti-climax, but the term imperfections is a very general one and covers a wide variety of different types of defect. These may be inherent to the metal or may be introduced during the manipulation of the metal by the constructor.

Before dealing with some of the more potent members of the family called imperfections it may be well to refer to the important properties of toughness and ductility. The precise nature of those properties cannot be entered upon, but a few remarks about them are really very necessary. For the present purpose at least they can almost always be regarded as related to one another. There are

cases in which ductility, as ordinarily measured, may exist in the absence of toughness, as ordinarily measured; but I know of no case in which toughness exists in the absence of ductility (even as ordinarily measured). Looking at the problem in another way, it may well be thought that toughness is nothing but an expression of effective ductility. Without ductility a metal cannot be tough, and if the material has ductility under certain conditions, but is so lacking in toughness that it cannot make use of its ductility, it might as well be non-ductile. Supremely, therefore, a metal requires toughness, as this property brings with it ductility, and what is more, the power to make effective use of its ductility.

Toughness and ductility values as ordinarily expressed in metals are generally inversely proportional to the strength values as ordinarily stated. Harden a metal, either by working or by quenching, and down go its toughness and ductility. Even by taking a variety of compositions of steel—suited to give a variety of strengths—the same general results are obtained, namely, that the higher the strength the lower the ductility and the toughness, and it is usually only possible to restore the ductility and toughness by removing part of the hardness. This is evident from the curves given in Figs. 4, 5 and 6.

It is also sometimes possible by heat treatment to increase the ductility and toughness of a metal that is fully hardened in such a way that its maximum stress is not materially decreased. Examples of this are shown in Table X.

TABLE X.

Condition.	Max. stress tons/sq. in.	Elongation per cent.	Red. of area per cent.
Work-hardened	72.0	5	18
Work-hardened and blued ...	72.9	10	37
Quenched	115	4	13
Quenched and tempered ...	113	10	31

The final remark that should be made regarding toughness and ductility is that both are affected materially by the condition of the metal. Cast metals have lower ductility and toughness than the same metals when forged, and the values of these properties "longitudinally" are markedly higher than the values "transversely," although the strength factors remain unaltered. This point is adequately illustrated by the figures given in Table XI. taken from one and the same metal.

TABLE XI.

	As cast.	Forged (longitudinal).	Forged (transverse).
Elastic limit tons/sq. in. ...	16.4	20.1	18.9
Max. stress tons/sq. in. ...	38.3	36.0	36.0
Elongation per cent. ...	19.7	33.1	23.5
Red. area per cent. ...	25.8	58.7	43.5
Impact foot lb.	16	86	29

(It is not without significance, I think, that the fatigue range is affected in much the same general way as the ductility and toughness, although the other strength properties remain unaffected.)

It seems reasonable then to draw the conclusion that ductility and toughness are increased by processes that soften a metal and reduced by processes having the reverse effect. Also they are improved by homogeneity (in the macroscopic sense), and by the greatest freedom from the disturbing effects of fibres and the

like. These conclusions have been drawn here because they must be applied to many examples of the disparity between " ideal " and " real " strength values.

Some of the " imperfections " can now be examined. One of the most potent is the group including slag, non-metallic inclusions, and the like. All these constituents of metals have their origin in the metal-manufacturing process and grossly affect the ductility of the metal, particularly when the ductility is called upon to operate in directions perpendicular to the slag streaks. In this direction the ductility is so much reduced by inclusions that a metal can rarely flow as much as is expected of it. Failure to flow is generally but another way of saying that the metal breaks—a thing that used to occur fairly frequently in the forming of spar sections from metal strip.

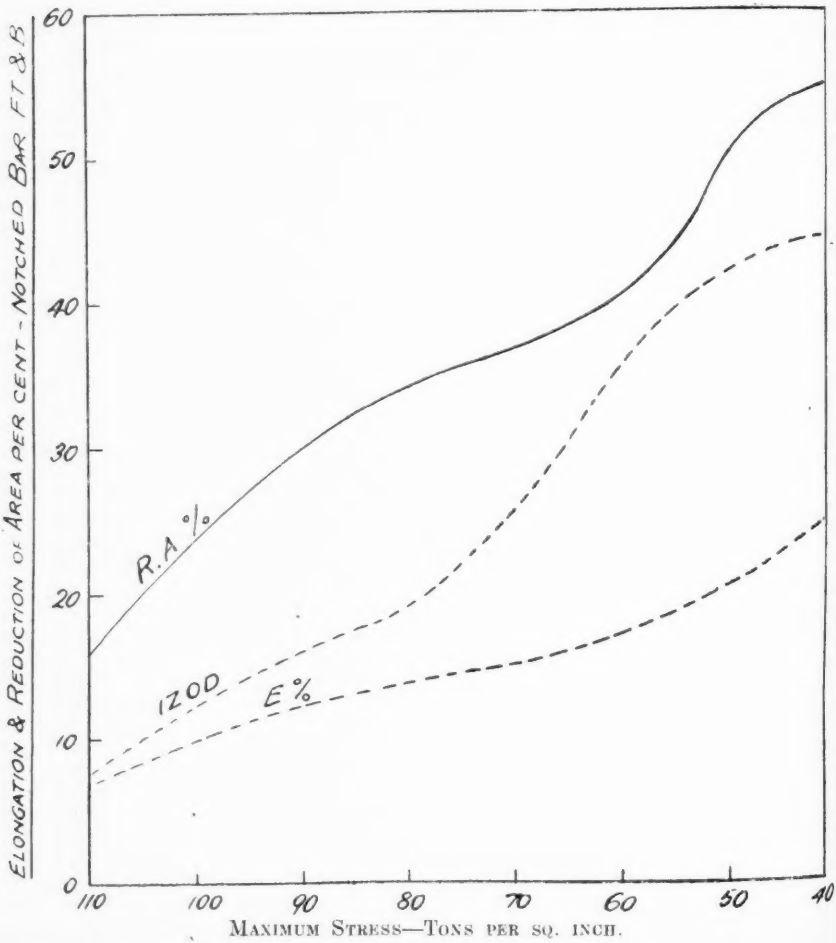

FIG. 5.—*Showing typical relationships between strength toughness and ductility of hardened and tempered steels.*

Roaks and contraction cavities that are rolled or drawn out to notable lengths are also metallurgical in their origin but should really be classed with such imperfections as cracks, splits and jagged edges in holes, rough machine marks, tears made during punching and riveting, and such like defects. It has been well established that the presence in a metal of any such defects affects very markedly the distribution of stresses within the metal. The general net effect is an adverse one and operates by markedly increasing the stress value in the part at the position of smallest radius in the imperfections mentioned. A roak or a contraction cavity can scarcely be distinguished from a ragged tooling mark or a tear around the periphery of a rivet hole, except that the profile is generally rather smoother and the liability to stress concentration rather less. It must be very evident, therefore, that all members of this class of imperfection are likely to be specifically harmful and to bring down the real strength of a part so materially as to constitute a notable menace to the safety of a machine for which the calculations have been made without taking such possibilities into account.

This is the point at which the toughness and ductility of the metal definitely may come into operation. When a stress is applied to a part, and by reason of notches or the like, it is unevenly distributed so that it has its maximum intensity at certain positions, the excess of the actual stress at these positions over the assumed mean stress in the part may be sufficient to cause the actual stress to

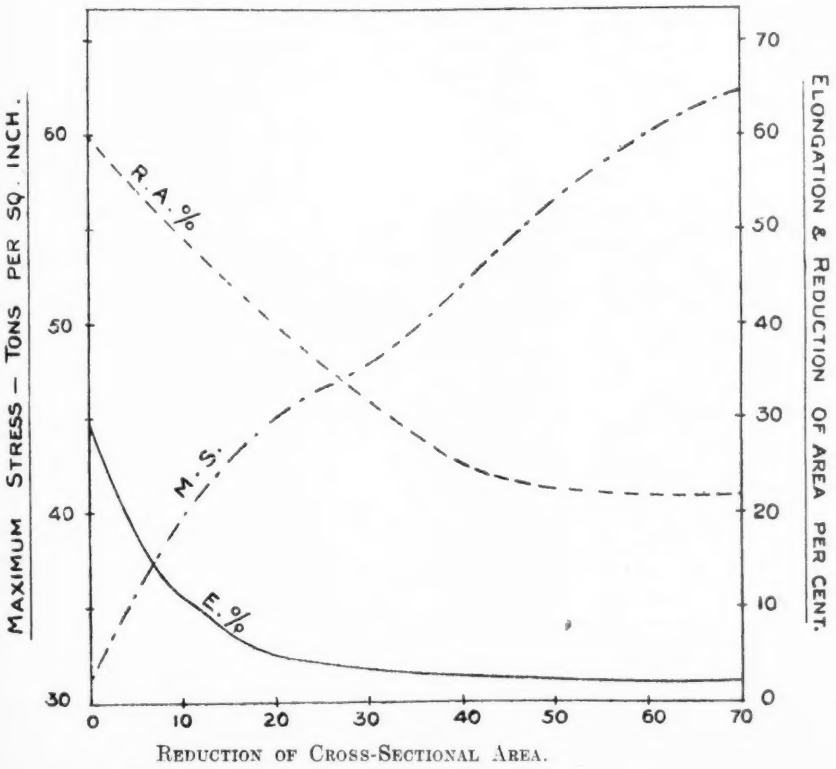

FIG. 6.—*Showing the effect of working in embrittling a steel.*

exceed the elastic limit of the metal materially. Granted that the metal has sufficient effective ductility, it will flow at the position of highest stress and will flow in such a way as to reduce the intensity of the stress at the considered point. In order to reduce the stress to a value lower than the elastic limit of the metal, quite a considerable flow may have to occur within the small element of metal that is actually subject to the abnormally high stress. This amount of flow can only occur in metals that possess adequate ductility and toughness. Unless the requisite flow occurs, fracture is almost sure to ensue, and in fact to intervene before the stress is reduced to a harmless value.

The importance of the presence of the necessary ductility is manifest. Consider two pieces of metal—one having half the ductility of the other. In many instances this might well mean the less ductile metal having approximately twice the tensile strength of the other. In the ordinary way the mean stress on the parts might be expected to be in general proportion to the maximum stress. The concentrating effects of the defect take no account of actual maximum stress, so that the local stress in one will be twice that in the other. In order, therefore, for the reduction of the magnified stress to come about by the flow of the metal, the same amount of plastic distortion must occur in both metals. With the more ductile metal the flow may occur and a satisfactory readjustment be brought about. With the less ductile metal this does not occur because the requisite ductility is not available, and before safety is reached the fracture of the metal occurs. This is a parallel case to that of Mr. Micawber's famous balance sheet, but is also a very good example of the paradox that "the stronger the metal the weaker the part."

The methods by which an adequate ductility can be ensured have been indicated already and need not be repeated. The main things to remember are that reheating after hardening is of great value in raising the ductility and toughness of a metal, and that for any given maximum stress (proof stress or the like) a certain combination of chemical composition and heat treatment brings about the highest accompanying ductility and toughness.

Besides the causes already mentioned that reduce the strength of a part, one other, namely, corrosion, must be considered. This process has two effects. Firstly it may generally reduce the strength of a part, but this effect is relatively unimportant. Secondly it may reduce the strength of a part very locally by the formation of a corrosion pit or a corrosion notch. Such defects will have all the bad effects of the other kinds of notch and at the same time may be more insidious as they are unsuspected because of their non-existence at the time that the part was made and inspected. It is clearly, therefore, amongst the less ductile metals that immunity from corrosion is likely to be of the greatest importance and value.

A further type of imperfection is one that is very frequently overlooked. This is the type known as internal strain or internal stress. Of this type of trouble a good deal has been written at one time and another, and those interested can consult the original writings. The presence of stresses within many parts bearing no external load is very well proved, and the magnitude of the stresses can be gauged from the fact that they are frequently sufficient to fracture a part that is standing quite idle. Usually, if not inevitably, such fracture occurs only in those parts in which there is a notch or corner that may act as a localiser for the stresses, but even so the average magnitude of the internal stress that will cause the spontaneous fracture of a die block weighing half a ton is by no means small.

The most prolific source of internal stresses is severe hardening—either by quenching or by working—and the former method of hardening is usually the more potent. In most instances the immediate cause is merely the uneven rates of cooling of different portions of the same article. This may sometimes occur even where there is no deliberate intention of hardening, a good example of such being in welding, whether of plain carbon steels or alloy steels. The only cure

for the welding trouble is a reheating of the whole article followed by regular and even cooling. For the internal stresses due to hardening the best cure is a tempering treatment at a fairly high temperature. This operates in a dual way, firstly by reducing the differences of volume that cause the stresses, and secondly by increasing the ductility and so making the flow of the metal more probable than its fracture. If the metal chosen has a suitable composition its maximum stress after the reheating will still be as high as is needed by the constructor.

The need of such a treatment is very obvious. If a part is already under stress, the further stress that can be put upon it without fracture can (in certain directions at least) hardly be greater than the difference between the existing stress and the maximum stress of the metal. The mere existence of the internal stress consequently very materially reduces the real strength of the part below that indicated by the ideal strength that is expected of the metal that composes it. As the incidence of high internal stresses is most frequent in metals of fairly high maximum strength, the intrinsic weakness of many parts made of "strong" metals is once again manifested.

The points that have been raised in the course of the above remarks have been intended to illustrate the ways in which the disparity between ideal and real values may arise. As stated at the beginning, these causes are not entirely unique to aircraft material, but become of greatest importance in this craft because of the smaller margin allowed for such like defects. Granted the existence of the defects or imperfections, the question arises at once as to whether the margin provided is sufficient to be safe. No simple answer can be given to this question. For some materials and under certain conditions the answer would be easily the opposite of that for other metals in other conditions. What is certain is that in general it is none too great, taking all in all.

A second question naturally arises when it is asked how may the margin be made most effective—or (what amounts to much the same thing) how may the defects be rendered most ineffective. Again there is no golden gospel that preaches salvation for all cases, but certain beneficial lines of action have been indicated earlier. In the first place it is a very good rule to decide that a material shall be used only in that state in which it possesses the most satisfactory combination of maximum stress and ductility. There are definite limits to the possibilities in respect of both types of property and these should be carefully respected. High maximum stress in the absence of adequate ductility does not constitute strength but weakness. Hardened metals—whether hardened by working as in aluminium or by quenching as in alloy steels—that have not been subsequently let down somewhat by reheating to suitable temperatures are not ductile or tough. The values of both properties can, however, be markedly improved by reheating the metal to suitable temperatures. The most suitable temperature depends upon the nature of the metal, the type of hardening, the degree of hardening, and the purpose to which the part is to be put, but it is a good and sound rule to make the reheating temperature as high as possible. Besides its direct effect upon the toughness and ductility of a metal, this process also has decidedly beneficial effects upon the elastic limit, proof stress, fatigue range and freedom from internal stress. For the purely metallurgical defects such as inclusions, nothing need be said here as the aircraft constructor cannot do anything practical with them that has any remedial effect.

The conclusion, therefore, to be reached is that for any particular strength there is a particular material that will best satisfy the requirements. There may be more than one material of course, but one is sufficient for the present purpose. It is the business of the aero constructor to choose the material that properly satisfies all the requirements, and not to try to achieve his ends by straining up a material which fulfils its proper functions satisfactorily at a lower position on the scale. If this selection is done properly a 60-ton steel is just as satisfactory and safe as a 25-ton steel, in fact for most purposes it is considerably safer.

It is possible to give some indication of what might be called a typical range of correlated strengths and compositions. This is done for steel only. The list is intended only to apply to the sizes of steel that maintain in aircraft parts. Otherwise, both heat treatment and composition might require to be altered somewhat. For each type of steel the range of maximum stress that is to be considered suitable is shown.

1. 22 to 30 tons, mild steel, normalised—carbon 0.25%.
2. 30 to 45 tons, medium carbon steel, normalised or hardened and tempered—carbon between 0.35 and 0.45%.
3. 45 to 55 tons, alloy steels, hardened and tempered
   (*a*) Carbon 0.3 to 0.4% and nickel 3%.
   (*b*) Carbon 0.15 to 0.20%, nickel 3.5%, chromium 1.0%.
4. 55 to 65 tons, alloy steels, hardened and tempered
   (*a*) Carbon 0.3 to 0.4%, nickel 3.5 to 4.5%.
   (*b*) Carbon 0.25 to 0.30%, nickel 3.0 to 3.7% and chromium 0.5 to 0.9%.
   (*c*) Carbon 0.20 to 0.25%, nickel 3.5 to 4.0% and chromium 0.9 to 1.2%.
5. 65 to 80 tons, alloy steels, hardened and tempered
   (*a*) As 4 (*c*).
   (*b*) Carbon 0.25 to 0.30%, nickel 3.5 to 4.5% and chromium 0.9 to 1.3%.

(ii.) Cold worked steels (which should be only used where no other is possible by reason of form, etc.), carbon 0.5 to 0.7 depending upon a very large number of factors.

When a choice of materials is made as above, and the steels in each particular selection are properly heat treated, the stronger steels are every bit as good as the weaker steels, and in fact are better. The exception is the very highly cold worked steels, though even here the deficiencies become practically negligible if the steel is properly heat treated after working. The danger in the very high tensile steel lies in the abuse of the methods that are employed to get the strength. If the metals are properly chosen, as suggested above, they will give the required maximum stress along with the best toughness and ductility. This is not abuse, but very much the reverse, and under these circumstances there is no doubt that for the majority of purposes the alloy steels with round about 55 to 60 tons maximum stress are far superior to all other types of material. A good nickel chromium steel, hardened and then tempered (at a temperature of about 630°C.) to give some 57 tons per square inch, presents a combination of strength, toughness and ductility, that would be hard to match among the known materials of engineering construction.

Discussion

The Chairman, in opening the discussion, said that the papers were encyclopædic in the quantity of material and data they contained. He expressed agreement with Mr. North as to the very great importance of the structure weight of an aeroplane, and also with his remarks as to the way in which the military equipment, often of unnecessary weight, was planted on the machine. This was his experience, particularly during the war, with regard to the mechanisms for carrying guns and bombs. Everybody would remember how enormously clumsy the Vickers gun was, and how much surplus weight there was on it, which could easily have been cut off, but the armament people never listened to any arguments which were put forward by the aeroplane people. They always said "Well, this is our standard thing; you have got to take it." He would have thought that 36 per cent., which was the figure given by Mr. North for the structure weight of the average aeroplane between 7,000 and 12,000 lbs. gross weight, was rather excessive. He would have thought that 30 to 33 per cent. would have been a

more reasonable figure. There was also the point that the performance represented by 10 lbs. per h.p., which was taken as the figure on which to base the machine Mr. North was thinking about, would be altered to some extent by the form which the aeroplane took. We were not so standardised that we could say that 10 lbs. per h.p. was going to represent a particular performance, whatever the aeroplane; at least, he hoped not. He asked Mr. North how near it was possible to get to the ultimate strength of the material with the sort of construction with which he was familiar. Supposing the material was a 70-ton material, how near could he get the main bulk of the material to that 70 tons? Referring to Dr. Aitchison's remarks on the fatigue of high-tension materials, the Chairman asked whether this sort of fatigue would be brought about by the vibrations of the engine or by the general handling of the machine. It seemed to him that we had no really solid data as to the effect of the high-speed vibrations of the aeroplane engine on a structure made of very thin high-tensile steel strip.

Mr. W. O. MANNING said that Mr. North's paper was a very able argument for the all-metal machine, and he believed that for many years past Mr. North had devoted all his time and energy to the development of that type of machine. It was not unfair to infer from that that Mr. North was not acquainted with the weights of the wooden machines being produced to-day, which, owing to several facts, were certainly lighter than those produced years ago. The structure weight he had given for an all-metal machine was 27 per cent. The only other figure that he had heard of which approached that related to a certain French machine —the Breguet fighter, mostly constructed of duralumin—which was stated to have a structure weight of 26 per cent. It would be interesting to know exactly what the factors were on the machine in question, and also what was included in that structure weight. There was always some doubt as to what should be included in the structure. Also, Mr. North had included the advantage that might be gained by the use of aluminium tanks, which, of course, were common to both types of aeroplane. Mr. Manning agreed with Mr. North that the question of joining these alumininum and light alloy tanks was not satisfactorily solved. With regard to vibration, mentioned by the Chairman, Mr. Manning said that this was very important in the case of these high-tensile steels. The vibration all over the machine would probably be much greater than in the case of a wooden machine. No doubt that would be got over by placing rubber buffers in various parts of the structure, or insulating the vibrating parts in some way, but it would be interesting to know if any trouble of that sort had occurred. It had been stated that metal sheet could be attached satisfactorily by soldering. He had experimented, however, with high-tensile steel, and had found difficulty in getting the solder to adhere properly. Mr. North had said that tanks might very well be made with stainless steel and other materials. He (Mr. Manning) agreed, and thought that the newer materials were very promising, but he did not think it safe to expect very much saving of weight in using them.

Discussing Dr. Aitchison's paper, Mr. Manning said he gathered that Dr. Aitchison took the view that the toughness of the material varied as the impact figure; in other words, an impact figure of 60 indicated a distinctly better steel than an impact figure of 40. Did Dr. Aitchison really mean that, as the general view seemed to be that, at any rate in the higher ranges, whatever such figures might indicate with regard to the effect of the heat-treatment process, they did not seem to indicate any engineering property by which one could say that one steel was better than another? As to internal stress, it was certainly difficult for the engineer to ascertain whether any material supplied to him for engineering purposes was to any extent in a state of internal stress. He would like to ask if it were true that if one found in the material a rather large difference between the elastic limit and the yield point, that might indicate internal stress. In conclusion, Mr. Manning thanked both authors for their valuable papers.

Major P. BISHOP said that both papers put forward a very strong case for

the use of more economic materials, and he considered that this policy should be keenly developed. It was not a new policy; the early constructors were fully aware of the advantages of the use of these materials. It was a policy that needed resuscitation at the present moment. The difficulties experienced in the early days in an attempt to introduce a better class of material were immense, and the war, in this respect, did not develop this particular aspect of design as much as it had assisted in other ways. There was, however, a very definite reason for this. Mr. North had vividly recalled the R.E.7 stampings from a weight point of view. He himself also recalled the difficulties with the same stampings from the material point of view. Those stampings were of material which fell into the "Medium Tensile Alloy" category, to use the authors' classification, and it was found that these could not be obtained in any consistent form at all; further, it was found that the heat treatment involved after stamping was practically an impossible proposition. This was due to the ignorance of the stamping industry at that time as regards metallurgical requirements. These difficulties resulted in a policy of reversion to what he might term the simpler materials; hence their standardisation. It is obvious that premature standardisation is always a drawback to progress, although probably essential to rapid production, and the development of aircraft design to-day is undoubtedly seriously handicapped for this reason. In regard to standardisation, he must take strong objection to one phrase used by Mr. North in his paper, namely: ". . . . Thanks to the initiative of the Royal Aircraft Factory, the aircraft industry was, many years ago, robbed of the international standard metric system." If Mr. North were more intimate with the internal affairs in those days he would find that the R.A.F. was one of the strongest advocates of the metric system, and did actually commence their standard on metric sizes. Unfortunately, the R.A.F., being an ordnance factory, came under the jurisdiction of the other ordnance factories, and was instructed to revert to the British units. It was another case of development handicapped by existing standards. As to the introduction of better-class materials to-day, there were many obstacles still to be overcome before full advantage could be taken of them. The first—and this was a very dangerous one to raise—was the question whether the industry and its kindred industries were sufficiently capable at the present time of looking after these more complicated materials. He said that without casting any reflection upon the industry, but it could not be denied that such materials required strict metallurgical control, and judging from the difficulties one experienced to-day in correctly controlling the more simple materials, this was undoubtedly a very important point, and must not be overlooked. Mr. North recognises in his paper that better personnel and equipment generally was necessary if factories were to embark on this policy. Another point which must not be overlooked is the fact that the substitution of high-tensile steel does not always result in a saving of weight. There were such items as robustness of design, the tolerances for manufacture, etc., which, in certain cases, demanded surplus material being added to the designer's original determinations, thereby nullifying any anticipated advantages arising from the use of high-tensile steel. A typical case was the smaller size of the old standard form of high-tensile forked end, which had to be stiffened up to meet manufacturing requirements. When stiffened up, it was found to be sufficiently strong in a lower grade of material. In raising this obstacle, he did not wish to give the impression that he was not an advocate of the use of these more economical materials, but he strongly recommended that precautions should be taken to prevent any sudden introduction of new materials before the industry was prepared to look after them.

In connection with Dr. Aitchison's paper, Major Bishop referred to the characteristics of the two stress/strain curves (Fig. 3), which resembled a cold-worked and a hardened and tempered material. He believed the Raf wire was a very good case in which both of these methods of manufacture had been fully explored. The Raf wire had, in the early stages, taken its form in a material of a

hardened and tempered condition, but the standard Raf wire was a cold-worked material. Perhaps Dr. Aitchison could explain why, after trying both of these particular schemes, the Raf wire had been standardised in its present form, *i.e.*, with characteristics as shown by the curve A.

Colonel RICHMOND commended both lecturers very heartily, especially for having refrained from dealing with more than one branch of the materials. He felt, however, that here should have been a little more advocacy of the wooden aeroplane, because wood probably possessed that prime quality which both lecturers had stressed, namely, it had done its job in the past as the best material then available, and there had been no question of straining up the properties of the material to suit the job for which it was required. With regard to the introduction of high-tensile materials, he considered they had reached the stage where they had fully justified their use, largely due to the development which Mr. North had very ably brought about. As to fatigue, he took it that Dr. Aitchison's remarks applied to the fatigue as carried out on a test specimen, and in the text of his paper he emphasised the caution with which the fatigue range values should be introduced into actual design. It was very difficult to say at this stage how far the designer could use the fatigue range, as obtained on a test specimen, as a criterion. Mr. Manning, who had raised the same question, probably knew that a large number of vibration tests had been carried out on completed components. The failures which had occurred in those cases were due to unsuitable design for the material employed, and they gave no indication that a light alloy was any worse than steel, or *vice versa*, in this respect. They did not indicate that the components were likely to fail at a stress seriously below that which had been calculated on by the designer. The question of Raf wires was a little distressing. There were quite a number of Raf wires coming in at present which were failing, undoubtedly under fatigue; they failed always in the same place, with the same type of failure. So much so that he felt it was hopeless to try to deal with this question by altering the material or endeavouring to initiate a standard tension or a standard setting-up of these wires, and that some attempt should be made definitely to stabilise the wire by some positive means against vibration. Another important point which arose—in connection especially with high-tensile steel wings—was the bonding which was necessary from the wireless point of view. It was very essential, so the wireless experts told us, that there should be no loose or semi-loose contact between the separate parts, and that, strictly speaking, every individual part, even although it may only be separated by a layer of stoving enamel, must be bonded. That provided quite a problem, and he would like to hear what proposals Mr. North had for dealing with that particular difficulty. Colonel Richmond congratulated both authors, and said that Dr. Aitchison's paper was truly encyclopædic—the sort of paper that would probably be found on the desks of a good many aeronautical engineers in the future.

Major BULMAN said that Dr. Aitchison's paper was extraordinarily concise, and one would wish that it could be circulated in the form of a calendar to all people who were engaged in any way with the purchase or use of steel. It would serve, at any rate, to dispel some of the mystery and doubt which seemed so often to affect and embrace the whole of the purpose and processes of heat treatment. The question of fatigue had been discussed from the point of view of the aeroplane; he considered it would be relevant to refer to the engine as well. Up to recently it had been sufficient, by eliminating the more obvious defects, to prevent fracture due to fatigue from occurring within a few hundred hours. Under present-day conditions, however, when we are already attaining something near a thousand hours' running, with prospects of still further increasing that figure, one must have some little apprehension as to whether or not we should come into a fatigue range without any obvious defect or cause; the accumulation of practical data which could be directed to this question would be most useful. At any rate, that matter of fatigue must further drive us to seek real and absolute soundness in

the material. Both authors had emphasised that an apparently "stronger" material might produce the "weaker" part. It was no good having a very high tensile material unless one was certain that the bulk of that material as employed in construction was truly represented by the selective tests carried out, and on which the design was based. He believed that general soundness of material could be achieved by concentrating the purchase and manufacture of material in a much smaller number of hands than it is in at present. It was within his personal knowledge that one particular type of steel employed by the aircraft industry of this country within the last nine months had been supplied by no less than twenty different firms. Obviously, the total quantity of steel used in British aircraft during the last nine months was relatively small, but when we divided that among twenty suppliers, the amount to be supplied by each of the firms could not encourage any one of them to exercise that extra care—"meticulous" care (using that term in Professor Haddow's special sense)—required to ensure uniformity and soundness in their products which must be provided if real advances in reliability are to be obtained.

The CHAIRMAN asked whether there was anyone present who could give information with regard to the actual use of duralumin in aeroplanes.

Commander J. C. HUNSAKER (U.S.A.) entered into the discussion in response to the Chairman's question. After expressing his pleasure at being in London and attending the meeting, he said that, with regard to duralumin, he believed we were all in the same boat; we were working with it, and its properties were interesting; we were making the pudding, and the proof was in the eating of that pudding. The time was a little too early for us to know how it would turn out. In the United States they had been impressed with the fact that the difficulties of construction with duralumin were less than the difficulties of construction with steel, probably because of the troubles with so-called "trick" steels—to use an Americanism. One of the speakers had expressed a doubt as to the ability of the aircraft industry to handle certain steels. In America they had had difficulty in getting and working strip. In the case of duralumin there was no difficulty in getting suitable strip, or in working it, if they kept down below about one-tenth of an inch. The matter of fatigue was still open to question. They had put pieces of cold-rolled mild steel sheets in special fatigue-testing machines, as well as duralumin, and the duralumin lasted longer in the machines than steel. Corrosion was a controversial point. The practice in America was to use varnish, and plenty of it. One point had occurred to him in connection with Mr. North's paper, namely, in regard to the structure weight of an aeroplane which had been given, that we must be careful not to regard that as a general figure which applied to all aeroplanes. All the percentages of structure weight ought to be restricted carefully to the types of aeroplane to which they applied. It was difficult to compare machines on the basis of their structure weight percentages, because there were other factors which had to be considered—such, for instance, as weight of power plant. An abnormally heavy power plant caused the percentage structural weight to appear very low, yet the aeroplane might not be lightly built.

Major MAYO, after congratulating the lecturers upon their most excellent papers, also referred to structure weight percentage. Commander Hunsaker had called attention to the fact that it might be a very deceptive matter to compare different machines on the basis of structure weight percentage. As Commander Hunsaker had said, the variation of power plant was one very important factor, but there was another which was often overlooked, namely, the loading per square foot of wing surface. Mr. Manning had also mentioned the question of relative strength. We had to take all those points into consideration before we could compare two machines on a structure percentage basis. For instance, if we had a machine with a given load per square foot, we got a certain percentage for structure weight, but if we added a considerable extra weight of useful load, which

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we could do perfectly well without greatly increasing the landing speed, we got a different value for the structure weight percentage. What he would like to know was how Mr. North had arrived at the two figures he had given, 36 and 27 per cent., and whether, in the two cases, he was taking strictly comparable machines. He (Major Mayo) agreed with the Chairman that 36 per cent. seemed unduly high for the machine of ordinary type construction. On the other hand, he was inclined to agree with Mr. Manning when he said that 27 per cent. seemed a low figure for the improved type machine.

Mr. North had said that the saving in structure weight that could be effected by using special steel construction was less important in the case of a commercial machine than in the case of a military machine. On the contrary, he (Major Mayo) ventured to say that it was even more important for the commercial machine. In the case of military machines, if we could not carry enough bombs on one machine, we sent two. The Government paid, and all was well. But in the case of a commercial machine, if we could not carry a useful commercial load, we could not continue to operate at all. With the machines used at present we were getting a total overall weight of about 16 lbs. per h.p. He believed that was accepted as the figure we could safely work to at present. That meant a useful load of only about 4 lbs. per h.p., and if we could effect a reduction in structure percentage weight of from 36 to 27 per cent. it would have a most important effect on the useful commercial load. It would be enough to make the difference between a financial failure and a profitable concern, and so it seemed to him that in future designs of commercial machines the question of employing metal construction or any other improved construction was of vital importance. But there was another aspect of the question, which unfortunately was very important, namely, that commercial machines could not be ordered in large numbers, as military machines could be. That had an important bearing on the question of what type of construction could be employed. The initial cost of the machine was of very great importance to commercial concerns, and the designer must consider whether it could pay to employ metal construction if the total number ordered was going to be limited to, say, a dozen machines at the most. That was the sort of proposition we had to think about at the moment, and he asked Mr. North if he would say, taking a machine with a total weight of, say, 10,000 lbs. or any other weight he cared to take, what minimum number of machines he would require to build to make the use of metal construction pay. If there were only two or three machines to be built, he was fairly sure that Mr. North would admit that steel construction could not be considered, but if there were fifty machines to be built, it would no doubt be worth while laying out the plant for steel construction.

Major BUCHANAN said his own experience was that aircraft designers in this country kept down their material to the lowest grade that they could possibly work with efficiently, because they were afraid of supplies. Generally speaking, even with the ordinary materials in use, very great difficulty was experienced in obtaining reasonably good supplies of steel. Dr. Aitchison might be able to give some information as to how that state of affairs could be remedied. He was very glad that the question of structure weight had been raised, because in his own experience he had found that the structure weight of aeroplanes generally was increasing. It was increasing because of the demands made upon aeroplanes, and also larger varieties of equipment were carried, and he believed it was beyond the skill of man to separate out the flying structure from the other with accuracy. The figure of 36 per cent. for the structure weight of a wooden aeroplane, he thought, was probably on the high side. He also shared Major Mayo's trepidation about the structure weight of 27 per cent., although he believed Major Mayo would remember—and he himself certainly remembered—an aeroplane which had the very excellent structure weight of 24.6 per cent. That aeroplane, he believed, was still flying. He also agreed with Mr. North on the importance of size. In these days, with the increased demands on aircraft, the increased load to be

carried, the increased performance and increased fuel consumption, aircraft were assuming larger dimensions, and shed accommodation was becoming a serious problem, apart altogether from the question of handling and manœuvrability in the air. He did not think Mr. North was quite fair to those on the equipment side. For himself, he had always found them very sympathetic, and they had always listened to reason. He believed that in the long run we should get down to lighter equipment. But the real reason why equipment was over-weighty at the present time was one which was familiar to all, namely, that war stocks still exist. When they were exhausted we should find an improvement. With regard to joining processes, Mr. North had put the case for sweating, when properly carried out, as being at least as reliable as glue in wood joining. He himself preferred to put it higher than that, because our experience, certainly in the East, had shown that glueing wood was thoroughly unreliable. Finally, Major Buchanan congratulated the authors on the excellence of the papers, and the Society on having been able to persuade the authors to put their experience on paper for the benefit of all concerned.

Mr. POLLARD referred to the statement in Mr. North's paper that high-tensile steel strip (S.40) could only be worked satisfactorily if under 22 G. His experience was, however, that the material could be used satisfactorily when thicker than .028in. It was merely a question of power required to force the material through the dies or rolls. Although the actual extension on the outer curve of the bend was greater in the case of the thick material, yet the strain was probably the same as for the thinner material, and consequently if the various radii on the dies were not less than that specified for the bend test for the steel, then no cracking would take place.

Further, he said that the thicker the material, the less the difficulty encountered in producing the various sections. Very thin steel strip, say, .01in. thick, could be very troublesome in forming to a uniform contour, owing to irregular "spring-back." In the case of strip .022in. and thicker, the necessary allowance for "spring-back" can be estimated with reasonable certainty.

As regards very thin steel strip, say, 17 G and over, it would probably pay to work the strip either hot, or perhaps cold but fully annealed, and continuously harden and temper in furnaces as the strip emerged from the dies or rolls.

Mr. Pollard thought Mr. North might be able to give them some information on this point.

REPLIES.

Mr. J. D. NORTH: Owing to the very limited time available, and the large number of points raised in the dsicussion, it was not possible for me to make an effective reply at the meeting. I, however, take the opportunity of publication in the Journal to give a more detailed reply in writing.

With respect to the points raised by the Chairman, firstly, that the 36 per cent. for the structure weight of the average aeroplane between seven and twelve thousand lbs. gross weight is rather excessive, for the purpose of calculating the structure weight I have deducted from the gross weight only those items appearing in the actual schedule of equipment, together with the weights of the propeller, engine, exhaust pipe, radiator system including cooling water, oil tanks and pipes, petrol tanks, pipes and cocks, ignition system, starting gear, and, of course, oil and petrol, engine cowling and fairing—in fact, the whole of the engine mountings have been included in the structure weight. This may explain part of the difference between my figure and Colonel Ogilvie's figure. Another point that has to be taken into account is the enormous amount of flooring, passage walkways, equipment installation, etc., which form a very large part of the structure. For example, it is typical of the class of day-bomber which I have

described to be provided for a crew of three with six different places where they can perform some different function, and these places have to be provided with floors, seating accommodation and so on.

With reference to power loading as influencing the performance, Colonel Ogilvie does not take my point here. What I said in my paper was that the necessary performance could *only* be obtained with a power load of 10 lbs. per h.p. By this I meant that, taking into consideration the limitations which military requirements would impose upon the design, and with the exercise of the best of our aerodynamical ingenuity, we could not carry more than 10 lbs. per h.p. and still obtain our performance; inferior aerodynamical design would not allow the performance to be obtained even at this power loading. However, for the purpose of comparing the "standard" and "light" aeroplane, I think I am entitled to assume equally efficient aerodynamical design in both cases.

On the subject of material strength, Colonel Ogilvie asked a question which was very difficult to answer in a few words. Where material is stressed in tension, *e.g.*, ties, the ultimate strength can be realised, but where the material is stressed in compression, effective compression strength can only be realised by appropriate design. Considerations of elastic instability impose a definite limit on the extent to which stiffness of struts can be carried; that is to say, a compromise has to be effected between F/c and L/k, the values for both of these influencing the weight of the structure. In only a few parts of the machine is it possible to make use of steel with an effective compression strength of 70 tons per square inch; such a stress, however, is regularly attained in spars, since they are subject to comparatively heavy loads, and in a limited number of struts on which the load is heavy considering their length. On reference to my paper, Colonel Ogilvie will see that I have not suggested the general use of materials of such a high tensile strength, but materials corresponding to those which I have suggested can be effectively incorporated in the structure; in other words, the saving in weight which one would expect from the specific properties of these materials can be realised.

With reference to his concluding remarks that there was no solid data as to the effect of the high-speed vibrations of the aeroplane engine on a structure made of very high-tensile steel strip, I would draw special attention to the fact that there has been no proposal to use very high-tensile steel strip. The highest tensile steel strip used in aircraft construction is B.E.S.A. S.40. This is really a medium tensile strip of good ductility, and there is nothing whatever to fear from the effect of high-speed vibrations unless the design is of such nature that the stress fluctuations induced by these vibrations exceed the fatigue range of the material. There are no *prima facie* grounds for discriminating between a structure of medium alloy steel strip or composite wood and metal structure so far as vibration is concerned, and I do not, therefore, feel myself able to agree with Colonel Ogilvie that this class is as obscure as his concluding sentence would suggest.

Mr. Manning also raises the question of the figure taken for the structure weight of the wooden machine, and states that owing to several facts, wooden machines being produced to-day are lighter than those produced years ago. This statement is somewhat surprising, in view of the fall-off in the specific properties of timber since the early days of Grade A spruce, and it is interesting to compare it with Major Buchanan's remark later on in the discussion—that the structure weight of aeroplanes generally is increasing. It is not unfair to suggest that Major Buchanan is in a position to take a wider view of the situation than Mr. Manning. In making the statement that the advantage gained by the use of aluminium tanks may be credited as well to the standard structure as the light structure, Mr. Manning rather misses the point, since aluminium tanks, not being a standard construction, are excluded from the standard structure by

definition. Needless to say, more economical materials can be introduced piecemeal into aeroplanes of standard construction with proportionate advantage, but this fact does not in any way controvert my argument that it is advantageous to use everywhere materials which will give the lightest structure. Mr. Manning goes on to say that vibration is very important with these high-tensile steels. I have already mentioned what Dr. Aitchison pointed out in his spoken résumé that these steels are not high tensile in the sense that ductility has been sacrificed for tenacity. That being the case, it is difficult to say why vibration is more important in machines constructed of alloy steels than in other material; on the contrary, these steels are particularly suitable for conditions where fluctuating stress is to be met with. With regard to Mr. Manning's statement that vibration all over the machine would probably be much greater than in the case of the wooden machine, I can only say that experience shows that it is not. On the whole, machines built up from riveted strip have been remarkably free from vibration; it is possible that with this form of construction, hysteresis is greater than would be the case in a machine built up of solid drawn tubes. With regard to soldering, I have experienced no difficulty whatever with the steels which I recommend in my paper. In the case of certain materials it is necessary to ensure that the surfaces are in a suitable condition for soldering, but in most cases cleanliness is the primary consideration.

I am pleased that Major Bishop finds himself in agreement with the policy which I have advocated. I agree with him that early constructors were to some extent aware of the advantages to be gained by the use of these materials, but the supply position is very much more favourable now than in the early days. The supply of alloy steels and light alloys in bar, strip, sheet and stampings is greatly improved, and it is in fact easier to obtain these higher grade materials, manufactured with a sufficient degree of accuracy and refinement, than it is to obtain the ordinary carbon steel sheets and bars in a condition suitable for aircraft work. This is not at all surprising since the higher class materials are nearer to the commercial requirements of the automobile industry. We have had, and I think it is a general experience, more trouble with steel such as S.1 and S.3 than with the alloy steels or light alloys. I am glad to hear from Major Bishop that the Royal Aircraft Factory was an agent and not a principal in the stamping out of the metric system in aircraft work. While I withdraw the suggestion that the initiative of the Royal Aircraft Factory was responsible for this policy, I regret that the Factory, which did so much to promote sound technique, was not in a position to initiate a more enlightened policy in ordnance circles. Major Bishop sounds a note of caution as to the immediate ability of the aircraft industry to look after what he calls these more complicated materials. No doubt evolution and not revolution is required, and there is therefore all the more reason for making an immediate start. It is certainly necessary to have a sound organisation and expert metallurgical advice, and in this respect I would take the opportunity of acknowledging the valuable help which I and my firm have received from Dr. Aitchison. The secret of successful heat treatment seems to me to be as follows:—Firstly, correct processes based on sound metallurgical grounds; secondly, capable supervision to see that these processes are adhered to; and thirdly, unskilled labour, which not having ideas of its own on the subject of hardening, I believe to be the safest. Major Bishop referred to limitations imposed by other considerations than those of stress in flight on the extent to which advantage can be taken of the higher specific properties of certain materials. It is true that the art of using these materials is not the art of the unjust steward to take your bill of dimensions and write down 50 per cent., and I agree with Major Bishop to this extent that the art of design is so to take advantage of the properties of materials as to retain adequate robustness, while using manufacturing processes suitable to the materials employed. My own experience shows me that given the initiative the means are available.

Colonel Richmond stated that wood probably possessed that prime quality, namely, that it had been regarded in the past as the best material. If we extend that argument, I put it to him that, in the neolithic age, stone was probably regarded as the best material, but I do not believe that Colonel Richmond really holds such reactionary opinions as to believe that what was best in the past is necessarily best for the present. It is not true to say that the properties of wood were not strained up to suit the job for which it was required, since the process of selection of timber was carried to such a pitch that it rejected far more than it accepted. I welcome Colonel Richmond's authoritative statement as to the position with regard to vibration tests, which I am pleased to say bears out the opinions on the subject which I have already expressed On the subject of Raf wire vibration, his suggestion for stabilising the Raf wires by some positive means certainly seems a rational solution of the problem, if a suitable means can be found.

On the subject of wireless bonding, I can only say in reply to Colonel Richmond's remarks that there is no evidence whatever that metal aeroplane parts joined together by rivets are not in continuous electric contact. Accurate measurements which we carried out some time ago definitely showed that in the case of metal aeroplanes which we had constructed the ohmic resistance was constant and unaffected by the application of steady or fluctuating external forces; until it is possible to conclude that this is not all which is necessary for wireless purposes, the question of further bonding need not arise. Any metal structure not riveted together, but definitely insulated by stoving enamel or some other organic protective, may require some special bonding to ensure electrical continuity; this, however, is a special case.

Commander Hunsaker's account of the difficulties in America with steel reminds me of the troubles which we experienced in England at the time when we did not really know what steels were wanted. The difficulty of getting and working steel strip in this country is now very much reduced; certainly the materials which we are using are straightforward steels, which can hardly come under the title of "trick steels." I agree with what Commander Hunsaker says on the subject of restricting structure weights to types of aeroplanes, but I cannot follow him when he says that heavy power plants mean light structure weights. Major Mayo also says that the weight of power plant has an important influence on the structure weight; I cannot see his point here, but his statement that surface loading has an important influence on structure weight is, of course, correct. This is kept constant in the comparison which I made in my paper.

On the subject of commercial aeroplanes I did not say that structure weight was less important on these machines than in the case of military aeroplanes; I merely said it was less startling. As a taxpayer I cannot accept his version of the economics of the Government, but I am pleased to hear that the metal aeroplane appeals to him as a commercial proposition. With regard to his specific inquiry, I certainly think that a dozen machines could be built economically—that is to say, at the same cost per passenger or per lb. useful load as the wooden machine; but the cost would depend to some extent on the total turnover, *i.e.*, if there were considerable numbers of military machines being manufactured at the same time, this would, of course, greatly help the commercial machines by reducing the standing charges.

In reply to Major Buchanan, I have already expressed my opinion that the policy of using low-grade materials with the hope of getting better supplies is unsound, particularly since the better-class materials are more easily obtained commercially in the quality suitable for aircraft. On the whole, I gather from Major Buchanan's remarks that he is in agreement with me. I should not, however, like him to think that anything I have said was intended to reflect on the equipment side of the Air Ministry. As he says, the matter is one of existing war stocks, and the responsibility, of course, falls on those who advise that these

war stocks must be used. Possibly this responsibility may be traced to the House of Commons, the members of which might be surprised to learn that it is not an economical way of disposing of surplus war stocks to build expensive aeroplanes to fly them about. Since every ounce saved in equipment means a saving of 10/-, conversely every extra ounce of equipment means another 10/- worth of aeroplane. I am glad to note that Major Buchanan considers sweating more reliable than glueing. In this connection I should like to mention that officially glued joints, *e.g.*, in propellers, laminated spars, built-up struts, and so on, are assumed to take load, though standard regulations do not recognise any addition of strength which sweating may give to riveted joints.

I understood Mr. Pollard to say that in his experience S.40 steel over 22 G. can be satisfactorily worked. I agree with him that there is no special difficulty in working this material, but in the thicker gauges it is rather more liable to develop stress cracks than a steel of the S.43 class, and is consequently less suitable for fittings. So far as forming this material into strips for spars is concerned, one cannot change the profile of thick material to the same extent as thin material without stretching the outer fibres more. For this reason the amount of change of shape which it is safe to put on in the way of cold working becomes more restricted as the thickness of the material increases.

Dr. AITCHISON, who had only time to reply to a few of the points raised regarding his paper, said that he wanted first of all to refer to the statements made with respect to Fig. 3. The materials used for the stress/strain curves given in that figure were rather more representative of unsuitable materials than of those that ought to be used. The curves were included for the specific purpose of indicating that two steels might have the same proof stress but differ in respect of almost all their other mechanical properties. He begged those who read the paper not to use the curves for any other purpose than that for which they were intended. He wished also to make it clear that if a cold-worked material had, after working, been so treated that it was relieved of internal stresses and also was suitably ductile, it should be considered as quite suitable to use. What he did insist on, however, was that no material should be used in aircraft which had been hardened and then left in that form without receiving the subsequent treatment that would on the one hand remove the dangerous internal strains, and on the other would remedy the dangerous deficiency of toughness and ductility that frequently existed in such material.

With regard to fatigue and the various points that had been raised with respect to it, Dr. Aitchison considered that the problem of fatigue in aircraft was on all fours with the corresponding problem in every other engineering circumstance. Whether fatigue stresses were set up in the materials by the normal stresses of the machine's work or were impressed upon them by the vibration of another part or from the engine did not seem to matter in the slightest degree. The material was being stressed, and the important stress was the algebraic sum of all those that came upon it. He thought that it had now been settled that, given certain specific types of stress, every material possessed a very definite fatigue range, *i.e.*, it was capable of withstanding an indefinitely large number of applications of the cycles of stress expressed by this range. With a variation in the condition of the material, or in the nature of the applied stress or in the components of the applied stresses, the actual fatigue range might be different, but for each set of conditions the value of the range was definite. Tests had been made with fatigue stresses running to about 1,000,000,000 cycles, and the results of these tests had shown no difference in the range obtained in these runs and those of about 10,000,000 cycles. The long run corresponded to about 10,000 hours of an engine running at 1,600 r.p.m. There appeared to be, therefore, a definite fatigue value which was possessed by a specific material in a specified state. Naturally if, during running, the real condition of the material changed, then the fatigue value changed too. Also a change of condition such as might be

introduced by the action of a corrosive atmosphere might readily affect the endurance of the material and cause it to have apparently an unduly low fatigue range. The breaking up of the surface of a material by corrosion is of very great importance in regard to its fatigue strength. In fact, even without an alteration of the surface, the fatigue strength of a metal might be lowered by the action of a corrosive atmosphere.

Mr. Manning had mentioned the need for a criterion as to the degree of freedom of a material from internal stress. He (Dr. Aitchison) would not care to say that the only reasonable criterion would be a marked difference between the elastic limit and the yield point, but if a material did show this difference, it was perfectly safe to conclude that the material was suffering from internal stresses. He had recently presented a long report on this topic to the Iron and Steel Institute, to which those interested might refer.

Mr. Manning also broached the relationship between toughness and the notched bar test. He (Dr. Aitchison) did not for one moment believe that the ordinary notched bar test would represent completely the toughness value of any material. Neither would he say that the toughness of two materials was directly proportional to the values given in a notched bar test. The values obtained in notched bar tests were very composite, and it was therefore fallacious to imagine that the real toughness of a steel that gave 60 ft./lbs. in the Izod test was fifty per cent. greater than that of a material which in a similar test gave only 40ft./lbs.

RADIAL AIR-COOLED AERO ENGINES.

BY A. H. R. FEDDEN, ASSOCIATE FELLOW.

A Paper read before the Royal Aeronautical Society (Scottish Branch).

1 *Introduction*

Although the static air-cooled radial engine is by no means an innovation in the history of aero-engine development, its career has been somewhat chequered. Some ten years ago several practical comparatively low-powered air-cooled radials were produced and successfully flown, but they were ousted by the rotary engine on the score of power/weight ratio.

When in 1917 it was found that the limit of the air-cooled rotary had been reached, a demand arose for an engine of the same characteristics of manœuvrability, compactness and light weight as this type, but of much higher power, and with a general all-round performance and fuel consumption comparable with the water-cooled engine of that date.

The most promising solution to the problem seemed to be the static air-cooled radial of 300-400 h.p., and much attention was drawn in 1918 to this type of engine. Several designs were developed, and although an excellent power/weight ratio was obtained, the promise given by these engines in the first preliminary stages was not fulfilled. Serious failures occurred, and designers of aircraft preparing new machines for these engines were disappointed and held up indefinitely for their power units; thus the static radial received a serious setback, and the impression was gained generally that this engine was inherently unsound, and not capable of being developed into a classic type. Following on these failures, as is so often the case when a particular design does not come up to expectations, the air-cooled radial went through a bad period, and much was said and written about its shortcomings and disadvantages. In spite of this disparagement, however, there were still people who believed that the air-cooled radial had great possibilities, providing proper time and care were taken to its special problems, with the result that after some years of experimental work the success of this engine is now an accomplished fact, and its performance as regards reliability, life, and fuel consumption is such that it must be reckoned with the best water-cooled engines of to-day.

Whereas it is not suggested that the radial is unequalled for all types of aircraft, and it is admitted that the successful development of this type of engine has been a long and tedious undertaking, and a certain amount of weight been conceded, nevertheless it is confidently believed that this engine will hold the field against all comers for certain classes of military and commercial work at any rate for the next ten years, in so much as a 400 h.p. production engine of this type, complete with propeller hub, exhaust manifolds, air intakes, etc., weighs 25 per cent. lighter than the very best water-cooled engine with the same equipment plus radiator and water, and within the next twelve months it will be possible to improve the power/weight ratio of the air-cooled engine on the same basis by a further 15 per cent.

It is proposed in this paper to shortly outline some of the advantages and disadvantages of the static air-cooled radial aero engine, and also attempt to analyse some of the problems peculiar to this engine.

2 *Advantages of the Radial Air-Cooled Engine*

As compared with accepted types of "in-line" and "Vee" type water-cooled engines, the static air-cooled radial affords certain distinct advantages, the most important of which are :—

(*a*) *Weight-saving.*—The question of power/weight ratio for the power plant of an aeroplane has always been of paramount importance; in fact, it was this quality of the internal combustion engine which made flying possible. This demand for a light engine is no less insistent to-day, and if comparison were possible, it is even more important for commercial than military aeroplanes. The author is strongly of the opinion that the aim of the aero-engine designer must be first and always the further saving of weight, and that the school of thought in favour of more weight is unsound, because any increase in reliability obtained would only give such an engine a very limited use. Although several ingenious and interesting designs offering very low power/weight ratio have been put forward of recent years, it is believed that certainly for powers up to 1,000 h.p. the static air-cooled radial offers by far the most promising field of exploration, and will do so until some revolutionary change is made from the present form of internal combustion engine.

(*b*) *The Elimination of Inertia Torque.*—The inertia torque on large engines due to the alternate acceleration and deceleration of the pistons and connection rods, with the consequent rapid alterations of stress in the crankshaft, is one of the most radical defects in the ordinary "straight-line" or "Vee" type aero engine. In multi-cylinder single-row radials, owing to the connecting rods all coming on to one common crankpin, this serious trouble inherent to "in-line" engines is practically eliminated.

(*c*) *Radial Engines* may be readily geared without interfering with the view of the pilot, maintaining the central axis for the propeller shaft, and also without meeting one of the main problems encountered when gearing down the propeller, viz., vibration due to inertia torque, which has been a prolific cause of the breakdown of many geared engines, so much so that certain forms of slipping clutch mechanism have been introduced to eliminate this trouble.

(*d*) *The Static Air-cooled Radial Engine* dispenses with the radiator, piping and water, with their attendant troubles. The failure of the water-circulating system on aero engines has by no means been eliminated; such troubles are still not infrequent, and from reliable data have been responsible for an appreciable percentage of breakdowns. Corrosion is also a serious problem on the circulating system of aero engines. For military and naval purposes, the elimination of water is important. In certain districts water may be very difficult to obtain. On certain classes of machines it may be necessary to leave the ground or the deck of a ship within a few seconds of starting the engine. The air-cooled engine has great advantages over the water-cooled engine in this respect.

(*e*) In very hot climates such as Mesopotamia, air-cooled engines have been found to give far better service than water-cooled engines for the following reasons :—An air-cooled cylinder will maintain full power if the mean temperature of the fin does not exceed 175°C. On the other hand, if the mean temperature of the cooling surfaces of a radiator exceeds 80°C., evaporation losses become considerable. Hence, in hot climates, where the air temperature may vary from 0°C. to 45°C., the temperature difference available for cooling may diminish 56 per cent. in the case of the radiator, whilst the diminution is only 25 per cent. in the case of the

air-cooled cylinder. Whilst this difference will do no harm to the air-cooled cylinder, the water will be boiled away rapidly in the radiator of the water-cooled engine. Conversely, in very cold climates, the air-cooled engine is even still more at an advantage, the difficulties of maintaining water-cooled engines in the field in winter in such countries as Norway and Sweden being a very serious problem.

(*f*) The static air-cooled radial can be made the shortest and most compact power unit it has up to the present time been possible to develop for an internal combustion engine working on the four-stroke cycle.

This advantage from the point of view of manœuvrability and saving of space is obvious, especially for military work; also the back plate of this type of engine affords opportunity for neatly and compactly arranging the auxiliary drives, thus protecting them from damage and weather conditions.

(*g*) An examination of the large static radial from a manufacturing point of view will demonstrate its great advantages in this respect. Nearly all the parts are symmetrical or round; there are no large difficult places to handle, or machine. A considerable proportion of the machining is in the form of large multiples. There are a fewer number of parts than in a " straight-line " or " Vee " type engine of equal power and performance. From the stores maintenance point of view, there are no bulky difficult pieces to handle and pack such as " in-line " crankshafts and crank cases.

It is believed that the production possibilities of the radial are not yet generally realised, and only when a really large production of this type of engine was required would there be the opportunity of demonstrating its manufacturing possibilities. Apart from the actual manufacturing facilities and ease of handling the parts, it is possible with a single-row static radial to eliminate castings altogether, should the output warrant it.

Engineers intimately acquainted with the problems and scrap figures of aluminium castings on modern aero engines will realise what this means. There is also the important question of deterioration of aluminium castings from corrosion and sea water, and the author is of the opinion that the possibility of producing an aero engine, eliminating castings altogether, and substituting light alloy drop-forgings, opens up very great possibilities.

(*h*) With the exception of the rotary, the static air-cooled radial can be dismantled, overhauled, and reassembled much more quickly than any other type of engine. This is a matter of considerable importance, both for military and commercial work. There are no water connections to make or break; there are no heavy complicated pieces to handle; there are no difficult or very skilled fitting operations. Recent maintenance figures, both from England and France, of proved water-cooled engines of high power, show the very considerable amount of time inevitably necessary with this type of engine for dismantling and re-erecting; this item is quite apart from the actual time and cost of effecting any repairs. This question is of the utmost importance on a fleet of engines for either military or commercial work. Examinations of valve timing, tappet clearances, carburettors, magnetos, and top overhauls can be readily made on radial engines, and this work can be systematically and safely undertaken in less time than it takes to prepare certain water-cooled installations for inspection. It is possible for two men to completely strip down ready for inspection a 400 h.p. radial air-cooled engine in

eight hours, and to rebuild in fifteen hours; these figures are being attained regularly in the engine shops of the Bristol Aeroplane Co.

(*i*) Providing the aeroplane fuselage is suitably designed, the single-row radial engine offers excellent opportunities for installation, no matter whether the engine is provided with a swinging mounting so that the back of the engine may be swung forward for examination and adjustment of the rear units, or attached to a pressed steel cone or tubular mounting. In either case the engine may be taken in and out of the machine in very much less time than is possible with an " in-line " or " Vee " type engine. The ease and rapidity with which a radial engine can be changed in the field is of the utmost importance on all classes of aircraft. The lay-out of a radial installation is such that mechanics can readily get at the engine to make adjustments without being hampered by radiators, water piping, engine bearers, control levers, etc.

3 *Some Problems Peculiar to the Air-Cooled Radial and How these have been Remedied*

In the preceding pages an attempt has been made to outline some of the main advantages obtained with radial engines for aircraft purposes. It is now proposed to deal with some of the special problems peculiar to the static air-cooled radial worthy of consideration, and which have been responsible for failure in the past. These may be classified as follows :—

(*a*) Insufficient cooling.
(*b*) Valve burning, wear and failure of valve mechanism.
(*c*) Excessive fuel and oil consumption.
(*d*) Unreliability and breakdown of big end bearing assembly.
(*e*) Crankshaft failure.
(*f*) Faulty installation.

These problems have been successfully dealt with by much careful experimental work at various sources, and one by one the troubles have been weeded out until the air-cooled radial engine is now able to take a prominent position. It is proposed to touch shortly on the various headings enumerated above, and to deal at greater length with the last-named, viz., installation.

(*a*) *Air Cooling Large Cylinders.*—The satisfactory cooling of large cylinders is by no means an easy proposition, and it was not until very careful and extended single-cylinder experiments were carried out under full load and working conditions that the problem was properly tackled. In considering engines with air-cooled cylinders of 45/50 h.p., it is believed that the designer has been faced with more practical difficulties than with other types of internal combustion engines, in so much as the disposal of the components to allow proper air flow, and the limitation of the foundry, are very real sources of trouble; consequently theoretical conditions have had to be sacrificed to a certain extent. The introduction and perfection of the new 11 m.m. diminutive sparking plug, eliminating hot spots and dead air, has also assisted the development of the air-cooled head. Cylinders have now been evolved with cooling area of not less than 25 sq. ft. per b.h.p., and .3in. pitch of fins which will maintain 123 b.m.e.p. continuously for certainly 250 hours without a breakdown.

(*b*) *Valves.*—Overhead valves are essential, and the arrangement of valves on large cylinders to give an adequate length of spring, together with proper air passages, calls for considerable scheming. Great strides have been made lately in valve material, and alloys of cobalt-chrome and

silchrome, and have been of great assistance in eliminating scaling and warping. The question of valve clearances is one of the utmost importance on radial engines. Push-rod mechanism for cylinders up to 6in. bore is certainly the lightest arrangement, but in the past great trouble has been experienced due to the cylinders "growing," with consequent abnormal clearances between valves and rockers, thereby greatly increasing the loading on all the valve-operating mechanism. This question was so acute that it bid fair to entirely destroy the reliability of radial air-cooled engines. Some method of automatically taking up the valve clearance as the engine warms up was absolutely essential.

This serious trouble with valve mechanism has been satisfactorily dealt with by the patent mechanism of the author's Company, whereby the valve automatically maintains the clearance set when the engine is cold.

(*c*) *Petrol and Oil Consumption.*—Both the petrol and oil consumption in air-cooled radials had been excessive in the past, due partly to overheating and bad distribution, and partly also to the special lubrication problems of radial engines. With the later development of air-cooled cylinders, and the elimination of hot spots, and the maintenance of more even temperatures, also by the careful investigation of induction systems and the improvement of distribution, it has been possible to very greatly improve the petrol consumption of radial engines.

On the earlier types of radials some difficulty was experienced with the over-oiling of cylinders. An attempt to cope with this defect was, in certain instances, made by the fatal mistake of cutting down the oil supply to the big end bearing; this has been proved to be entirely the wrong way to attack the problem.

The maximum volume of oil is necessary to keep down the temperature of the big end bearing, and by the correct design of the crank case to drain away the oil and the use of efficient scraper rings, the oil consumption has been greatly reduced and brought into line with other types of aero engines.

(*d*) *Big End Bearing Assembly.*—The big end bearing assembly of the static radial air-cooled engine requires very careful design, and the early types were, for the most part, very inadequate, and quite incapable of giving long service. These failures were due to too high loadings, heavy moving parts, lack of stiffness, and unsuitable lubrication. It is believed that the plain bearing offers the best solution, as it is lighter, the rubbing speed can more easily be kept down, and with this type the articulated rod pin centres can be kept nearer the centre of the crank pin.

By careful attention to reciprocating parts, the employment of special light alloys for pistons, and providing the maximum oil circulation to reduce the bearing temperature, it is possible to obtain a big end construction with a mean load factor of 10,000 lbs. per sq. in./ft. per sec., which will give an excellent life, comparing favourably with other types of engines.

(*e*) *Crankshaft.*—In single-row radial engines the desire to incorporate a nose to the engine which may be suitably cowled in, and present a good form, has led designers to prolong the propeller end of the crankshaft. Now, although the natural period of the single-throw crankshaft is usually well above the running speed of the engine, there is a wide range of speed over which torsional vibrations are intensified, and it is essential that the propeller shaft end shall be as short and stiff as possible, so that

the natural period is far removed from any possible running speed of the engine.

(*f*) *Installation.*—Although the author does not wish to make excuses for the delinquencies of the static air-cooled engine in the past, it is submitted that many of the earlier air-cooled radial engines were seriously hampered by incorrect installation, which was probably due to the novelty of the problem, and to the fact that attempts were sometimes made to instal radial engines in machines originally designed for other types. These failures have led aeroplane designers to have a false impression of the possibilities of the air-cooled radial.

It is not sufficient to mount an engine so that an ample volume of air from the slipstream of the propeller and the forward movement of the machine impinge on to the cylinder head, if this air is not able to get away. This is not possible when cylinders are mounted close up against bulkheads, as there is not adequate opportunity for the air to escape.

In like manner, it is impossible for an air-cooled radial engine to function properly if individual cylinders are unevenly cooled, sparking plugs pocketed, etc. From actual flight tests it has been found that comparatively slight alterations to the shape of the cowling have resulted in a remarkable difference in engine performance. To obtain the best results from an air-cooled radial engine, the whole installation requires to be approached from a new standpoint without prejudice, and necessitates the elimination of many preconceived ideas on the subject.

There is a divergence of opinion amongst aircraft designers as to the general form of cowling for radial engines on similar types of aeroplanes, that careful combined wind tunnel and full-scale experiments are necessary to definitely establish standards. Suitable engine mountings may be constructed in either tubular or pressed steel form, the former type being the lighter and the most easily adapted to different shapes of fuselage.

In either case the base should be as large as possible, and the back plate of the engine well forward from the fireproof bulkhead of the machine, to allow accessibility for the magnetos and oil pumps, and also to provide proper air flow for the cylinder heads. Where pin joints are used, these should be a ground taper fit with reasonable bearing surfaces.

Cowlings should be made readily detachable in panels and sufficiently robust to prevent cracking. The single-row radial offers far more facilities for neat and workmanlike cowling than the double-row type.

For high-speed machines operating at altitude some form of variable shutter cowling is required, controlled by the pilot, and working in conjunction with an electric galvanometer.

Spinners, although adding to the appearance of the aeroplane, are a constant source of trouble in service, and a doubtful quantity as regards improving performance.

On new types of machines it is advisable to carry out preliminary flight tests with an electric galvanometer, and temperature readings should be taken on individual cylinders to prove out the general form of cowling. By this means much time will be saved in arriving at correct running temperatures.

Although radial air-cooled engines are more susceptible to change of oil temperature than water-cooled engines, which is not disadvantageous under certain circumstances, nevertheless this fact is no justification for the haphazard installation on the oil system generally.

Oil temperature recorders and controllable oil coolers should be fitted. The latter can be arranged neatly in tubular form inside the cowling without appreciably increasing drag or weight. Both for the pilot's comfort and to make night landing possible, some adequate form of exhaust system is necessary. The design of a suitable manifold requires careful consideration and must be properly tested out and standardised. Expansion joints are necessary to prevent cylinder head distortion, and rustless iron can be used with advantage to prevent scaling and corrosion.

An interesting type of cowling for single-row air-cooled radial engines has recently been tested out in England on the test bed and flown in France, with considerable success. This is not a new scheme, and it was originally put forward by Mr. Robert A. Bruce of the Westland Aircraft Company some three or four years back.

The scheme consists of cowling the engine down to the crank case, and fitting over the cylinders separate helmet cowls, which can be supplied with controllable shutters and individual silencers.

By this means the view and performance of the machine may be considerably improved, and, in the opinion of the author, further enhances the value of the air-cooled radial for military purposes.

Providing attention is given to the special problems of an air-cooled radial, no matter whether swinging or fixed mountings are used, the aeroplane designer can arrange for the power unit to be dismantled in far less time than is possible with any other type of engine.

4 *Air-Cooled Engines at Altitude*

Speaking generally, the same difficulties are present with air-cooled engines at altitude as with water-cooled engines, but owing to the importance of supercharging aero engines it is proposed shortly to refer to this question.

The air speed of an aeroplane falls off very considerably at height, due to decrease in engine power owing to decreased density, and this occurs in spite of the fact that the power required to maintain constant air speed diminishes the higher the altitude.

Of the various methods of supercharging air-cooled radial engines, the author is of the opinion that the exhaust-driven turbo compressor is the most promising.

To obtain really satisfactory results, the whole engine design requires to be specially conceived for the purpose from the outset, and the blower cannot successfully be added to an existing type.

Additional heat problems must be faced, but this type is self-regulating, and is not subject to mechanical gearing and engagement difficulties, increased fuel consumption, etc., which must be faced with the geared type of blower.

It is estimated that the net increase in weight of a 400 b.h.p. air-cooled radial engine with an exhaust-driven turbo compressor will be 15 per cent.

As an intermediary step, however, it is considered that high-compression air-cooled radial engines employing the bi-fuel system offer a promising solution. Alcohol fuel is used with this scheme, and successful tests have already been made with 7 to 1 compression ratio, the temperature being less than with a normal compression engine.

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5 *Conclusions*

In the foregoing pages the author has endeavoured to outline some of the main points in the design of air-cooled radials, the special problems to be dealt with in this type of engine, and the present state of its development.

In view of the great improvements made in the reliability and performance of air-cooled cylinders on radial engines, it has been suggested to the author that the "Vee" type of air-cooled engine should receive further attention. The author is not in favour of this view, and is of the opinion that the future of air-cooled engines is in the radial form. A reversion to the "Vee" type sacrifices the weight-saving only possible with the radial, and introduces the undesirable problems existing in "in-line" engines, such as long crank shafts, large heavy crank cases, etc. The question will undoubtedly be asked what is the immediate future for the static air-cooled radial engine, especially in view of the fact that most of the classic endurance and racing performances during the last five years have been made with water-cooled engines. The answer to this question is—that all these important performances have been made with engines developed during the last war, when unlimited brains and money could be spent on them; that only since the war has the static air-cooled radial engine received the necessary attention and investigation, and only within the last twelve to eighteen months has this engine been able to really take its place in the front rank with the best water-cooled engines.

What, then, is the immediate future of the air-cooled radial engine?

Although it is generally considered unwise to prophesy on mechanical matters, the author seriously submits that in the light of results already obtained, the static air-cooled radial has a remarkably bright future, and that for some years to come this type of engine will have no serious competitor, and will stand alone for the following types of machines:—

1. For light aeroplanes with engines of one to two litres.
2. For training machines, taxiplanes, and the smaller passenger machines with three, five or seven cylinders of six to nine litres capacity.
3. For single-seater and two-seater fighting machines of all classes.
4. For deck landing machines, and the smaller float type seaplanes.
5. Generally for machines in extremely hot and cold climates.

It is impossible to say how much further the field will open out for air-cooled radial engines as time goes on, but until some entirely new type of internal combustion engine is perfected, it is confidently believed that the air-cooled radial engine will steadily be used in greater numbers, as its advantages are more fully realised by practical experience, and it is further developed.

Up to the present time the air-cooled radial engine has not been used to any considerable extent on large machines, but some very successful experiments have already been made, and the author is of the opinion that, especially for three-engined machines, the air-cooled radial offers a promising solution and many advantages.

REVIEWS

Ergebuisse der Aerodynamischen Versuchsanstalt zu Gottingen

L. Prandtl, C. Wieselsberger and A. Betz. Vol. I. (1921) and Vol. II. (1923).

The laboratory at Göttingen, under the able direction of Dr. L. Prandtl, is the chief centre of aeronautical research in Germany. The modern vortex theory of aerofoils, which will always be associated with the name of the director, is typical of the high standard of the theoretical work carried out at the laboratory, and the present volumes contain a wide range of experimental investigations of equally high standard. The wind channels are of a distinct type with open working section and closed return circuit, enabling ready access to the model without the necessity of a closed working chamber. The detailed description of these wind channels, together with the control mechanism and measuring apparatus, is of particular interest owing to the marked difference from the methods used in this country.

The chief interest for the aeroplane designer will probably lie in the tests of 94 aerofoils contained in the first volume. The series covers a wide range of different types and some of the thick aerofoils show remarkably good characteristics. In comparing these results with standard British tests, it should be remembered that the German aerofoils are tested with an aspect ratio of 5, and that the drag is therefore higher than would be obtained with aspect ratio 6. A further point of interest is the test of six aerofoils to a high scale ($LV = 250$), revealing in every case a marked scale effect in maximum lift and minimum drag.

The volumes also contain a brief account of the vortex theory of aerofoils, relating to the effect of aspect ratio of monoplanes and to the induced drag of biplanes. The experimental results confirm the theory in the first case, but it appears that the biplane theory requires extension from its simple form to allow for the curvature of the flow. Another deduction from the theory has been an estimate of the influence of the boundaries of the air stream on the flow past an aerofoil, and the theoretical deductions have been confirmed by suitable experiments

On the more academic side lie the experimental results on the skin friction of flat surfaces and on the drag of spheres, cylinders and simple geometrical forms. These results are, however, of considerable interest and importance, and reveal scale effects of unexpected magnitude.

In addition to these principal researches, the volumes contain a number of experimental results relating to particular problems—the pressure distribution round a few aerofoils, the effect of proximity to the ground, and the interference between a wing and an airscrew or fuselage. The presentation of the results in figures and tables is always good and the standard of accuracy, whenever it can be checked, appears to be high. These two volumes are the first of a series in which the work of the Göttingen laboratory will be published, and the appearance of further volumes will always be awaited with considerable interest.

The Mechanical Properties of Fluids

A Collective Book by C. V. Drysdale, Allen Ferguson, A. E. M. Geddes, A. H. Gibson, F. W. Hunt, Horace Lamb, A. G. M. Michell, G. I. Taylor. (Blackie & Sons, Ltd., 20/-.)

The present work is a collection of essays by highly qualified writers on the mechanical properties of fluids, and has been published with the hope of making the recent discoveries in this branch of science more generally known, especially

to the practical engineer. The method of treatment is to present in the earlier chapters theoretical and experimental considerations of fluid flow, and then to show how such investigations contribute to industrial development. This purpose of the book has been successfully achieved; it is impossible to read the book without appreciating the value of fundamental researches. Regarded as a general survey of the subject, the book is also satisfactory and cannot fail to interest the general reader.

It would seem that another purpose of the book is to whet the appetite, so that the treatment is perhaps not sufficiently comprehensive to satisfy the specialist who would desire to read original papers, to which references are, in general, given in each section.

The reviewer does not agree with the view expressed in the Publishers' note that the mathematical notation has been made uniform, *e.g.*, the symbol " ω " is much overworked, and represents the specific volume of water, cross section and angular velocity. Also there appears to be some unnecessary overlapping between the several chapters. Why have sections on viscosity in Chapters I. and II. when a large part of Chapter III. is devoted to the same subject?

The book opens with a chapter by Dr. Allen Ferguson on liquids and gases, in which the more important general properties of fluids are discussed. This essay is very excellent in itself, but seems to be somewhat isolated from the rest of the book; one ventures to suggest that it might have been better to have assumed on the part of the reader a knowledge of general principles. It is thought that the selection of material for this chapter must have been difficult, owing to the wide scope of the subject.

Chapter II. contains an introduction to the mathematical theory of fluid motion by Professor Lamb, the method of treatment being similar to that adopted in his classical treatise on hydrodynamics. The problems considered include vortex and wave motions, and so are of direct practical interest.

The important subjects of viscosity and lubrication have been excellently treated by Mr. A. G. W. Mitchell. The theory of viscous flow between plane surfaces and in capillary tubes is given and various types of viscometers are described. The chapter closes with a consideration of Osborne Reynolds' theory of lubrication, with applications to actual bearings. The bibliography of original works on viscosity of fluids and the viscous theory of lubrication should be of service to the reader who is particularly interested in this subject. Streamline and turbulent flow, considered largely from the experimental standpoint, is the subject of Chapter IV., the author being Professor A. H. Gibson. Reference is made to Dr. Hele Shaw's well-known experiments on the fluid flow between parallel glass plates, and to the experiments of Osborne Reynolds, in which the existence of a critical velocity was first demonstrated. The results of the classical experiments by Stanton and Pannell on air and water flow in pipes are also included; these experiments showed that the shape of the curve obtained when $R/\rho V^2$ (R is the resistance per unit area) is plotted against Vd/ν is independent of the diameter of the pipe and the type of fluid. The chapter concludes with sections on the measurement of the velocity of flow in fluids, and on the effect of fluid motion on heat transmission. Professor Gibson also contributes a chapter on hydrodynamical resistance, which should be of direct interest to both the aerodynamical engineer and the naval architect. At the outset a dissertation on dimensional homogeneity and dynamical similarity is given, which has, of course, a direct bearing on model experiments. This is followed by sections on skin friction and the resistance of both wholly and partially submerged bodies. Attention is also given to the scale effect and resistance of plane surfaces, of wires and cylinders, and of strut sections. The statement that the resistance of an airship body is approximately proportional to the square of the wind speed needs further qualification, since model experiments in a wind tunnel have shown an appreciable

scale effect on well-shaped airship forms. One would have liked to have seen included the resistance coefficients for good streamline shapes, since they are surprisingly low compared with bluff-shaped forms of the same size.

The theory of wave transmission of energy and other phenomena due to the elasticity of a fluid are contained in Chapter VI. An essay by Professor G. I. Taylor on the determination of stresses by means of soap films is given in Chapter VII. A mathematical discussion of the method is first given, and this is followed by a description of the apparatus designed at the R.A.E. by Professor Taylor and Dr. A. A. Griffith. The value of the method is illustrated by applications to various typical problems in engineering design, such as the determination of the torsional stresses in an angle beam and a hollow shaft with keyway. The intricate problem of wind structure is treated at some length by Dr. A. E. M. Geddes in Chapter VIII.

The chapter by Dr. Drysdale on the comparatively new science of submarine signalling and the transmission of sound through water cannot fail to interest the general reader. The various devices for sound transmission and reception are described in detail; the author has certainly achieved his purpose of showing the great importance of underwater acoustics. The last chapter in the book on the reaction of the air to artillery projectiles has been written by Mr. F. R. W. Hunt. A brief account of the history of ballistics is given, and this is followed by sections on the effect on drag of the shape of a projectile and on the general character of the motion of a spinning shell. One strongly doubts the accuracy of the curves of Figs. 4 and 5, which show at and above the velocity of sound an exceedingly large scale effect on drag coefficient; in view of the author's statement that these results are probably not very reliable, it is thought that they should have been omitted.

In conclusion, the book can be strongly recommended to all who are interested in the mechanical properties of fluids; it has only to be read to be assured of a place in the most exclusive scientific library.

A. F.